DOCUMENT RESUME

ED 115 308 IR 002 861

AUTHOR	Ballard, Richard J.; Eastwood, Lester F., Jr.
TITLE	Planning Communication Networks to Deliver Educational Services.
INSTITUTION	Washington Univ., St. Louis, Mo. Center for Development Technology.
SPONS AGENCY	National Aeronautics and Space Administration, Washington, D.C.; National Science Foundation, Washington, D.C.
REPORT NO	WU-CDT-M-CG-75-6
PUB DATE	Aug 75
NOTE	162p.
EDRS PRICE	MF-$0.76 HC-$8.24 Plus Postage
DESCRIPTORS	*Cable Television; Closed Circuit Television; Computer Assisted Instruction; Computer Programs; *Delivery Systems; Educational Specifications; Educational Technology; Estimated Costs; *Facility Case Studies; Information Networks; Information Retrieval; Lecture; *Networks; State of the Art Reviews; Telecommunication
IDENTIFIERS	*Dedicated Coaxial Cable Networks; Missouri (Saint Louis); PLATO; TICCIT

ABSTRACT

As companion to the more general document Telecommunications Media for the Delivery of Educational Programming, this report concentrates on the technical and economic factors affecting the design of only one class of educational networks, dedicated coaxial cable systems. To provide illustrations, possible single and dual dedicated cable networks are considered as ways to deliver educational services to selected institutions in the St. Louis metropolitan area. The networks described have the capacity to simultaneously distribute 35 forward and eight return channels. Cost estimates, construction techniques, and technical limitations of the systems are discussed in detail. Since user efficiency is a key factor in minimizing the cost of the system, a projection is made for the potential use of the system in the St. Louis area. Extensive appendixes concentrate on the technical functioning of the system. (EMH)

****
* Documents acquired by ERIC include many informal unpublished *
* materials not available from other sources. ERIC makes every effort *
* to obtain the best copy available. Nevertheless, items of marginal *
* reproducibility are often encountered and this affects the quality *
* of the microfiche and hardcopy reproductions ERIC makes available *
* via the ERIC Document Reproduction Service (EDRS). EDRS is not *
* responsible for the quality of the original document. Reproductions *
* supplied by EDRS are the best that can be made from the original. *
****

ED115308

CENTER FOR DEVELOPMENT TECHNOLOGY

WASHINGTON UNIVERSITY
SAINT LOUIS, MISSOURI 63130

Memorandum No. CG-75/6 August, 1975

PLANNING COMMUNICATION NETWORKS TO DELIVER EDUCATIONAL SERVICES

by

Richard J. Ballard
Lester F. Eastwood, Jr.

U.S. DEPARTMENT OF HEALTH,
EDUCATION & WELFARE
NATIONAL INSTITUTE OF
EDUCATION

THIS DOCUMENT HAS BEEN REPRODUCED EXACTLY AS RECEIVED FROM THE PERSON OR ORGANIZATION ORIGINATING IT. POINTS OF VIEW OR OPINIONS STATED DO NOT NECESSARILY REPRESENT OFFICIAL NATIONAL INSTITUTE OF EDUCATION POSITION OR POLICY

This study was supported by the National Science Foundation under Grant No. EC-38841 and by the National Aeronautics and Space Administration under Grant No. NGR-26-008-054. The views expressed in this memorandum are those of the authors and do not necessarily represent those of the Center for Development Technology, Washington University, or the sponsoring agencies.

IR 002 861

TABLE OF CONTENTS

No. Page

1. Introduction 1

2. An Illustration of the Deisgn and Analysis of Educational Communications Networks. 6

   2.1 Cable and Amplifier Factors Affecting Network Design. 6

   2.2 Installation and Routing Factors Affecting Designs 14

      2.2.1 Routing. 14
      2.2.2 Installation Factors 17

         2.2.2.1 Aerial Installation 17
         2.2.2.2 Installation in Underground Conduits. 18
         2.2.2.3 Direct Burial Installation. . . . 19

   2.3 A Dedicated Coaxial Cable Network Design for the Saint Louis Metropolitan Area 20

      2.3.1 Selection Criteria for Institutions to Receive Network Services 20
      2.3.2 Layout of the Network. 25
      2.3.3 Types of Installation to be Utilized . . . 29

   2.4 Cost Estimates for a Dedicated Network Design for the Saint Louis Metropolitan Area 30

      2.4.1 Cost of the Network. 31
      2.4.2 Costs of Equipment 41

3. An Analysis of the Services Able to be Offered on the Dedicated Educational Network. 46

   3.1 Introduction. 46

   3.2 Determining Communications Costs of the Dedicated Cable Network 46

   3.3 Technical and Economic Factors Affecting the Types of Services Offered on the Dedicated Educational Communications System. 49

      3.3.1 Televised Lectures with Interactive Remote Audio Capability. 49
      3.3.2 Central Refresh TICCIT CAI Services. . . . 58
      3.3.3 Remote Refresh TICCIT CAI Services 64

TABLE OF CONTENTS
(continued)

No. Page

3.3.4 Community Information Services 70
3.3.5 PLATO IV Computer Aided Instruction Services 71
3.3.6 Distribution of Prerecorded Videotapes . . 75
3.3.7 Facsimile Retrieval of Documents from a Central Data Source. 79

3.4 A Comparison of the Services Able to be Offered on the Dedicated Educational Network. 83

4. Summary and Conclusions. 89

4.1 Purpose of the Report; Relation to Other Work . . 89

4.2 Summary of Findings 91

APPENDICES

Appendix 5.1 Technical Considerations in the Design of Coaxial Cable Communication Networks . . 97

5.1.1 Introduction. 97
5.1.2 Cable System Design Considerations 97

5.1.2.1 Signal Degradation Due to Noise 97
5.1.2.2 Signal Degradation Due to Distortion. . . . 101
5.1.2.3 The Effects of Received Signal Level Upon Signal Quality 108
5.1.2.4 Limits to Cable System Length and Channel Capacity 109

5.1.3 A Coaxial Cable Network Design Example 120

5.1.3.1 Introduction 120
5.1.3.2 Designing the Return Video Network. 121

5.1 Bibliography 137

TABLE OF CONTENTS
(continued)

No. Page

Appendix 5.2 Specifications of the Components Used in Designing the Example Networks. . . . 138

5.2 Bibliography 148

BIBLIOGRAPHY. 150

ACKNOWLEDGMENTS 153

LIST OF TABLES

No. Page

1. Institutions Served in the St. Louis City Area 22
2. Institutions Served in North St. Louis County. 23
3. Institutions Served in South and West St. Louis County 24
4. St. Louis City Cable Network Costs 34
5. North St. Louis City Cable Network Costs 36
6. North St. Louis County Cable Network Costs 39
7. South and West St. Louis County Cable Network Costs. . 40
8. Equipment Required at Headend and on Premises to Interface Programming into Cable Network 42
9. Estimated Cost of the Cable Distribution Network Serving the St. Louis Metropolitan Area --- Return Video Network. 44
10. Per Channel Hour Communication Costs for the Single Cable Return Video Network Serving the St. Louis Metropolitan Area. 50
11. The Estimated Cost of Providing Televised Lectures . . 59
12. The Estimated Cost of Providing Central Refresh TICCIT Services. 65
13. The Estimated Cost of Providing Remote Refresh TICCIT Services. 69
14. The Estimated Costs for a 1008 Terminal PLATO IV CAI System on the St. Louis Dedicated Educational Network. 76
15. The Estimated Costs for a 4032 Terminal PLATO IV CAI System on the St. Louis Dedicated Educational Network. 77
16. Capital and Communications Requirements of the Services Able to be Offered on the St. Louis Dedicated Educational Network. 84
17. Costs on a Per User Contact Hour Basis of Services Able to be Offered on the St. Louis Dedicated Educational Network 87

LIST OF TABLES
(continued)

No. Page

APPENDICES

5.1.1: Summary of Expected Level Variations as a Function of Component Selection and Construction Type. . . . 115

5.2.1: Signal Attenuation as a Function of Cable Size and Dielectric. 139

5.2.2: 24 db. Interamplifier Spacing as a Function of Cable Size and Dielectric 139

5.2.3: Typical CATV Amplifier Performance Specifications . 141

5.2.4: Typical 1972 Coaxial Prices 143

5.2.5: Typical 1975 Amplifier Costs. 144

5.2.6: Typical Construction Costs. 145

5.2.7: Typical Construction Costs. 146

5.2.8: Typical Construction Costs. 147

LIST OF FIGURES

No. Page

1. Institutions Served in the St. Louis Area 26
2. Institutions Served in North St. Louis County 27
3. Institutions Served in South and West St. Louis County. 28

1. INTRODUCTION

In our previous work concerning educational technology, (1) the types of educational services that might be delivered using telecommunications technology were discussed. Using these services, learners in traditional academic environments could receive instruction in subjects not otherwise available at their particular institution, and could self-schedule their own instruction in many cases. In addition, people could receive instruction at remote locations, such as their place of employment; thus education could be available to many for whom conventional classroom attendance was too inconvenient.

The high initial cost of educational technology makes it advantageous for the cost of the services to be shared by as many users as possible. This sharing requires that a communication network interconnect the users of the services. Depending on the type and amount of services required, and upon existing facilities that may be available, the network can have many forms. The type of network ultimately used also depends upon the size and location of the area throughout which the services are to be distributed.

Leased telephone lines, low power UHF transmitters, point-to-point microwave relay, and CATV network channels are now being used to deliver educational services in one form or another. (2, 3) It is beyond the scope of this memorandum to examine the engineering and economic details of all of these communication networks; the details are available in engineering literature or from the associated common carriers. What we can do, however, is to examine one of the network types in an effort to demonstrate the types of details that must be considered in designing an educational network. This memorandum discusses the technical and economic tradeoffs that must be considered in designing a dedicated coaxial cable network.

Coaxial cable networks are a particularly interesting design example for several reasons. First, cable's high bandwidth (typically up to 274 MHz in two bands, one covering frequencies from fifty to three hundred MHz, and a separate band from six to thirty MHz) could distribute much diverse programming over entire metropolitan areas. Moreover, in many cases, a cable network might have enough capacity to support future expansion of network services without requiring additional cable construction. In addition, because the literature describing cable television network design is fairly complete, most of the technical and economic factors affecting network design can be examined in detail. Finally, because much of the cost of building a cable network lies in construction costs that are independent of the number of cables being installed (e.g., the cost of repositioning wires on existing poles for aerial installation, or the cost of digging and refilling trenches in the case of buried cable construction), a second dedicated cable system could be installed at great savings if it were built at the same time that a commercial CATV system were being installed.

Coaxial cable has many advantages that allow the educational network designer to provide users with more services than could be carried over a different transmission medium. Because of the design of the cable, signals on the cable are not only protected against outside interference, but the signals carried on a cable are confined within the cable. This is especially important in urban areas where the available frequency spectrum is already being used. Without cable's shielding properties interference would limit the quantity of educational services deliverable.

In the networks presented in this memorandum, not only can programming originated at the headend be received with acceptable quality, but in addition, programming originated by any of the institutions served by the network can be received with acceptable quality at any other institution served by the network; this allows students at remote locations to view lectures as they occur, using a portion of the network's return bandwidth to interact with the lecturer. Remote viewing of lectures would allow working students to attend classes more conveniently while allowing area colleges and universities to share the load of teaching basic courses. The networks can also carry services derived from centralized programming sources such as CAI and remote document retrieval services.

When used with our previous memorandum describing the types of services that may be offered using communications technology (1), this memorandum serves as a guide for the design of educational networks. Having discussed possible services in the previous memorandum, in this memorandum we illustrate the technical and economic tradeoffs involved in network design by designing and costing single and dual cable dedicated educational networks to serve selected institutions in the St. Louis metropolitan area. The network's five spokes can each carry up to thirty-five, six MHz bandwidth channels of programming per cable from the headend to the spoke's users, while up to three channels of video programming per cable can be simultaneously originated by the institutions served by a single network spoke. In addition, digital signals originating at any institution served by the network can be received with acceptably low bit-error rates by any other institution served by the network.

Having designed the network, we then examine the cost of offering each of the educational services able to be delivered. We determine the cost of the equipment required to offer each service, and we estimate the salaries of personnel required to provide each service. As a means of illustrating the actual cost of each service, a "per user contact hour" cost is determined. Furthermore, after outlining the communications requirements of each educational service, we show how these communications requirements limit the amount of services able to be provided.

It is hoped that by illustrating the considerations involved in determining the types and amounts of services that can be provided, future network designers will find here a guide that will assist them in the engineering design of educational networks. It should be pointed out, however, that to design an actual network the user needs of the area would need to be determined first. The networks for the St. Louis area presented here are intended to illustrate the technical principles of coaxial cable network design and to allow estimates of the cost of providing each educational service to be made. Therefore, no survey of the area's needs was undertaken; instead, a set of institutions potentially able to support the networks were identified, and the cost of providing services to users at the institutions was estimated. As such, the networks presented here are not intended to represent partial solutions to the educational needs of the St. Louis metropolitan area. We do, however, offer first estimates of the cost of providing educational services to institutional users in the

St. Louis area, and, using the information presented here, the design of more representative dedicated networks for the St. Louis area could be made.

2. AN ILLUSTRATION OF THE DESIGN AND ANALYSIS OF EDUCATIONAL COMMUNICATIONS NETWORKS

2.1 CABLE AND AMPLIFIER FACTORS AFFECTING NETWORK DESIGNS

The main components of a coaxial cable system are the cable itself and the amplifiers used. The optimal system design utilizes the least expensive combination of these which will provide an acceptable quality signal over the required distance, given the temperature ranges of the area to be served. The signal quality is primarily a function of the amount of noise and distortion products added to signals passing through the system, which in turn are related to the distance to be covered. The qualitative effects of noise and distortion on network design are discussed in this section.*

Coaxial cables are available in three sizes and with two different types of dielectric. The cable consists of a copper or aluminum center conductor encased in a cylinder of insulating dielectric. The dielectric typically is composed of polyethylene or styrene foam plastic. Around the dielectric, a woven or solid outer conductor is wrapped, and then the entire cable is encased in one or several layers of insulation and cladding designed to protect the cable from environmental degradation. The choice of cable is interrelated with the choice of the amplifier system selected. The factors to be considered when selecting the appropriate combination are discussed below.

Like all transmission media, coaxial cable attenuates the signals it carries. The degree of attenuation is a function of the type of dielectric used, the size of the cable, the frequency of the signal being carried, and the temperature in which the system is operating. If a coaxial cable network is to cover any appreciable distance, amplifiers must be spaced periodically along a cable link to compensate for the cable's attenuation and maintain signals at a usable level. Ideally, these amplifiers would only increase the signal's intensity, so that the output of the amplifier would be an intensified version of the input. However, amplifiers also degrade the signals in several ways. A quantity of thermal noise is generated in each amplifier, and added to the output signal. As the number of amplifiers in a cascade increases, the amount of noise added to the signal also increases, thus decreasing the signal-to-noise ratio (SNR). As the SNR decreases the received signal is increasingly degraded. In digital transmissions, this results in an unacceptable bit-error rate; in television transmissions, the result is a "snowy" picture.

---

*For a quantitative analysis of how system noise and distortion affect network design, see Appendix 5.1.

The amount of noise generated in any particular amplifier is relatively constant under typical operating conditions, so an acceptable SNR can be maintained in several ways. First, the number of amplifiers in a cascade can be reduced by using better quality (and more expensive) coaxial cable. Better cable attenuates the signal less, therefore requiring fewer amplifiers to cover a given distance. Alternatively, the level at which the signal is propagated through the cascade can be increased. If the noise generated within the cascade remains constant, increasing the signal level will also increase the system's effective SNR. For a given length cascade, there is a minimum signal level which must be maintained if an acceptable signal-to-noise ratio is to be insured.

Nonlinearities in amplifiers' transfer characteristics also degrade the signal by causing distortion. Ignoring thermally generated noise for the moment, an amplifier's transfer characteristic ideally would be given by

$$V_{out} = a_1 \times V_{in}, \qquad (2.1)$$

where a_1 is the amplifier's voltage gain. Real amplifier transfer characteristics are more closely approximated by

$$V_{out} = a_1 \times V_{in} + a_2 \times (V_{in})^2 + a_3 \times (V_{in})^3. \qquad (2.2)$$

For the "well-behaved" amplifiers typically used in coaxial cable transmission systems, $a_1 >> a_3 > a_2$. The nonlinear terms of the transfer characteristic have several effects upon the quality of signals propagated through the cascade. These terms generate second- and third-order intermodulation distortion products which, if of significant amplitude and close in frequency to one of the channels carried on the cable, cause beat interference. This results in a visible "herringbone" interference pattern on a received television signal. (4)

Amplifier nonlinearities also cause cross-modulation distortion, so that instead of being constant, the amplifier's instantaneous gain is a function of the input signal's instantaneous amplitude. Because video information is impressed upon a television signal by varying the instantaneous amplitude of the carrier upon which the video signal is being transmitted, an amplifier's gain varies as the carried signal levels vary. If more than one channel is being carried on a cable network, the amplifiers' varying gains can result in one channel's modulation being weakly impressed upon another channel, and vice versa. If the interference is strong enough, slanting bars will appear in the picture of a received television signal. If all of the signals on the cable have synchronous timing (i.e., are derived form a common source), the slanting bars will be stationary. More commonly, the signals' timing will be derived from several sources of slightly different frequency and the slanting bars will wander horizontally across the received picture, giving a "windshield-wiper" effect. (4)

The system designer can reduce the amount of second- and third-order distortion generated within a cascaded amplifier system in two ways.* Since the total distortion generated within a cascade is the sum of the distortion generated in each cascade amplifier, minimizing the number of amplifiers needed will minimize the distortion added. Again, using higher cost cable with less attenuation will minimize the number of amplifiers needed.

The second method to reduce second- and third-order distortion is to decrease the level at which signals are carried within the system. Referring to equation 2.2, if the signal voltage (V_{in}) coming into an amplifier is doubled, the voltage of the desired linear term of the amplifier's output signal, $a_1 \times V_{in}$, is also doubled, but the voltage of the squared term $a_2 \times (V_{in})^2$, is increased by a factor of four, and the voltage of the cubic term, $a_3 \times (V_{in})^3$, is increased by a factor of eight. Thus, increasing the level at which signals are carried within the system decreases the system's signal to distortion ratio (SDR) and makes the interference caused by distortion more perceptible. Conversely, decreasing the level at which signals are carried within a system increases the SDR and makes the interference caused by distortion less perceptible. The principal result is that for a given system, there is a maximum level at which signals can be propagated within the system if excessive second- and third-order distortion interference in the received signal is to be avoided.

---

*A third but less desirable method to reduce the amount of distortion and noise generated within a cable link is to reduce the number of channels the link will carry. This reduces the cable transmission bandwidth required and therefore the highest frequency that must be carried on the system. Because the cable's signal attenuation decreases with decreasing frequency, interamplifier spacing can be increased and fewer amplifiers in cascade will be needed to span any given distance, thus reducing the total amount of noise and distortion generated. Furthermore, because the amount of distortion generated depends upon the number of channels available which can combine to form spurious products, the amount of distortion generated in each amplifier is reduced. However, since the ability to increase service later without building a new system is desirable it is preferable to design for the maximum number of channels the cable can carry.

Given that there is a minimum level above which signals must be maintained if excessive degradation due to noise is to be avoided, S(min), and a maximum level below which signals must be maintained if excessive degradation due to second- and third-order distortion is to be avoided, S(max), consider what happens when additional amplifiers are added to a cascade. Each additional amplifier generates additional noise, increasing the total amount of noise generated within the cascade. If a given minimum SNR is to be maintained, the value of S(min) must be increased by an amount equal to the increase in total system noise. Similarly, each additional amplifier increases the total amount of distortion generated within the cascade. If a given minimum SDR is to be maintained, the value of

S(max) must be decreased enough that the reduction in generated distortion compensates for the additional distortion generated in each amplifier added to the cascade. It can be seen that as more amplifiers are added to the cascade, the value of S(min) will increase while the value of S(max) will decrease until at some point, S(min) will be greater than S(max). When this happens, the maximum number of amplifiers that can be cascaded will have been exceeded and no signal level will allow signals of acceptable quality to be received.

In an ideal cascaded amplifier system where signal levels remained constant regardless of the environment in which the system was operated, the maximum amplifier cascade size would be the number of amplifiers at which S(min) = S(max). However, signal levels can vary because amplifiers' gains vary as their components age, and because cable's signal attenuation varies 1% for every 10°F. change in temperature. (5) Thus, the number of amplifiers cascaded in a system must allow a sufficient range between S(min) and S(max) so that system signal levels can vary without causing excessive signal degradation. Simons (4) denotes the difference between S(min) and S(max) as the system's "tolerance." Since as the tolerance increases, the range of levels over which the system can acceptably operate also increases, tolerance is a measure of the system's quality.

The amount of tolerance required in a system depends upon several factors. Amplifiers incorporating automatic gain control (AGC) and automatic slope control (ASC) are available to intersperse with regular amplifiers to compensate for signal level variations. However, they are effective only over a limited range of input level variations. Since systems are designed so that excessive variations cannot occur, the range of variation over which the AGC amplifiers used can compensate determines the maximum tolerance needed in the system. Given this maximum tolerance the proportion of AGC amplifiers used in a system can usually be adjusted to enable the system to cover the distance desired. With a higher proportion of AGC amplifiers, the signal levels are adjusted more often and the maximum possible signal level variation can be reduced. This decreases the system tolerance required and allows more amplifiers to be cascaded without excessively degrading received signal quality. Further, using more AGC amplifiers than is minimally necessary will result in even better quality signals being received at the cascade's end.

Most cable networks will probably also need to use one additional type of amplifier. This is a bridger amplifier. A bridger amplifier serves several functions. First, it amplifies network signals and allows the signals carried on a single cable to be fed into two or more cables where necessary without causing excessive signal level reduction. Second, a bridger amplifier isolates the forward channels on the branches from the return signals, so that noise generated in one branch cannot interfere with signals in another.

The incremental cost of adding bridging facilities to a repeater amplifier is less than the cost of a separate bridger amplifier. Therefore, savings will result if a repeater amplifier with bridging capabilities can be installed instead of a separate bridger amplifier at the point where the spoke branches. However, in some cases it might be uneconomical to locate a repeater amplifier at the exact point that the branches diverge, but quite reasonable to have one near the divergence point. In that case, the designer would install additional cables from the amplifier with bridging facilities to the point where the cable branches separated. This would only occur, however, when the cost of the multiple cable construction was less than the savings realized by not using a separate bridger amplifier.

For the network designed in this report minimum acceptable video performance specifications for a signal received anywhere in the network are:

Signal-to-noise ratio = 43 db. (NCTA)
Maximum allowable cross-modulation distortion = -51 db.
Minimum received signal level = 0 dBmV.

The signal-to-noise ratio is referenced to a 4 MHz noise bandwidth and is measured with respect to the level of signals' sync pulses. Similarly, cross-modulation distortion is measured with respect to sync level. By maintaining the received signal level above 0 dBmV, individual receiver noise figures should not noticeably affect the amount of noise discerned in received signals. (11)

Digital signals are much less susceptible to interference from noise and nonlinear distortion than are video signals, so that a channel capable of propagating video signals acceptably can also carry digital signals without causing excessive bit-error rates. Therefore, this design assumes that the network is only required to carry video signals. If educational services requiring digital data transmission are to be included among the services available, part of the network's bandwidth can be reserved for digital signals.

However the type of equipment needed to interface digital signals onto the cable network is highly dependent on the particular services offered. Therefore, considerations of interface equipment will not be included in the designs of the cable networks but rather in the next Chapter along with the amounts and types of educational services that can be carried on a network.

The effects of noise and distortion buildup on received signal quality are examined more closely in Appendix 5.1. Equations specifying the amount of noise and distortion that can be expected to be generated under worst case conditions are developed, and worst case conditions for both aerial and underground construction are specified. One of the networks presented in this Chapter is then analyzed to illustrate the use of the equations derived. The equations and example network analysis give the reader all of the information required for the technical design of dedicated cable networks. Together with the price information given in this Chapter, Appendix 5.1 allows the network designers to accurately estimate the cost of a cable network serving their particular needs.

2.2 INSTALLATION AND ROUTING FACTORS AFFECTING DESIGNS

The design of a coaxial cable network must take into consideration a number of factors concerning installation and routing. These factors are affected by the specific location of the system and the climate of the area, and are important to determining the appropriate cables and amplifiers to use.

2.2.1 Routing

Theoretically the most desirable route for a cable is a straight line between each two points to be connected. However, conditions in the area the cable is to pass through and existing cable facilities will determine the actual route selected.

In most urban areas, the telephone and electric power companies are allowed to install their cables almost wherever they must. They have government authorization to do so because if permission from each owner whose property cables would cross were required, for all practical purposes the utilities would never be able to provide services to the public. However, a dedicated educational network would not automatically be classified as a public service. Therefore, the network's operators would not necessarily receive permission to install their cables wherever needed.

Building separate facilities for a dedicated network is not usually practical. In urban areas, concrete would have to be broken up and replaced all along the route to install conduits or directly bury cable, or poles would have to be installed for aerial construction. Both are expensive. A more practical alternative is to install cables on the poles and in the conduits already used by the utilities. Separate cable facilities could be built only where necessary. The St. Louis telephone and electric power companies have agreements permitting their respective cables to be installed on the poles and in the conduits belonging to either company. (7) The cost of excavating and refilling the trenches required for direct cable burial is also shared by both companies. Network operators would have to come to agreement with both the telephone company and the electric power company before their cables could be installed in existing facilities. (7) Under such agreements cable operators usually are responsible for all construction costs incurred when installing cables on utility poles and in utility conduits, and have to pay a monthly or annual rental fee. If network operation ceases at some future date, the network's operators would also be responsible for removing the network's cables from utility facilities at that time.

Routing network cables through existing facilities might require that a less-than-optimal cable routing be used, especially when utility-owned facilities did not exist along the best routes for installing cables. In some cases, existing facilities along the desired route might already be so filled with utility cables that installation of additional network cables would be impossible. This crowding is particularly a problem in older, large cities. To minimize routing problems, a network designer needs to work closely with utility company planning engineers when initially designing a network utilizing existing facilities.

The network described in this report assumes that network cables can be installed along area streets, roads, and railroad right-of-ways.* In places where the network's cables must cross obstacles such as rivers and limited access highways, routing is constrained so the cables cross the obstacles at existing traffic overpasses. The latter routing assumption has been previously made in a design study of broadband dedicated networks for use in the Dayton-Miami Valley area. (8)

---

*In an effort to make the routing of the networks discussed in this report as realistic as possible, the permission of the telephone company to examine their cable routing records was requested. Unfortunately, permission was denied.

2.2.2 Installation Factors

There are three types of installation for coaxial cables: aerial installation, direct burial installation, and installation in underground conduits. Naturally, when a choice is possible, the least expensive type is usually chosen. Most often, however, the type of installation used is dictated by the amount of development in the region and by the type of installation used there for utility cables. It is quite likely that a single network will include all three types of installation at different places along its routes. In all three cases substantial savings can be realized if additional cables for future expansion are installed at the same time as the first.*

2.2.2.1 Aerial Installation

Aerially constructed cable systems have several characteristics that suggest the types of components that should be used when constructing aerial portions of a network. First, there is a limit on the number of cables that can be installed on a utility pole. Most commonly, the number is determined by utility or cable company specifications for minimum spacing between coaxial cables and utility cables on utility poles. For practical purposes, the size of the cables to be used are unaffected. Further, except for the higher cost of the larger diameter cable itself, the cost of constructing aerial cable systems is unaffected by the size of the cable. (9)

---

*The costs of the different cable construction methods are discussed in Appendix 5.2.

Thus, use of a large diameter cable might be desirable since the savings realized in using fewer repeater amplifiers to cover a given distance might more than offset the cable's higher cost.

Aerially constructed cable systems are directly exposed to weather, and therefore the system must be designed to operate acceptably under extreme temperature variations. The cable itself must be encased in a waterproof jacket and sufficient insulation. Since the cable's potential attenuation variance is great, the level at which signals are carried in an aerially installed system must be controlled more carefully than in an underground system. Amplifiers with the added expense of AGC/ASC circuitry must be used exclusively. Again, if high-quality, large-diameter coaxial cable is used its additional cost is more than offset by the savings realized from using fewer expensive AGC/ASC amplifiers to cover a given distance. Thus, in designing the aerial portion of the system, the task is to select the optimal combination of cable size and quality and number of AGC/ASC amplifiers which will minimize costs and provide an acceptable quality signal.

2.2.2.2 Installation in Underground Conduits

There are several technical characteristics which must be considered when installing cables on existing conduits. First, some existing conduits might be nearly full, necessitating the use of a smaller diameter cable, inspite of its higher signal attenuation. In addition, as Weinberg (9) reports, as well as the cost of the cable itself being less, the cost of installing smaller diameter cables in underground conduits is less than the cost of installing larger diameter cable. Further, conduits are usually located 4 feet underground. Thus cables are subjected to less extreme temperature variations than an aerially constructed system. As a result, the cable's attenuation varies less as a result of temperature variations, and signal level control in the underground portions of the system is less critical. Thus although a smaller diameter cable requires more repeater amplifiers in cascade to cover a given distance than a larger diameter cable, several advantages are possible. If all the amplifiers used in the cascade have AGC/ASC circuitry, more amplifiers than could normally be cascaded can be used without causing excessive signal deterioration. This in part compensates for the cable's higher attenuation. On the other hand, if the distances to be covered are short enough, it might be possible to alternate AGC/ASC amplifiers with less expensive manual gain amplifiers, compensating in part for the cost of the greater number of amplifiers required by the smaller diameter cable.

2.2.2.3 Direct Burial Installation

Direct burial of cable is likely to be more expensive than either aerial or conduit installation. Trenches have to be dug and refilled each time a new cable is to be installed. This makes it especially important that if direct burial construction is to be used, enough cable capacity be installed when the system is being initially built to accommodate expected future expansion of network.

The number of cables that can be installed by direct burial is not limited by conduit size or pole capacity. However, according to Weinberg, (9) larger diameter cables are more expensive to install in trenches. Further, the type of cable used in direct burial installations is more expensive than either the cable used in aerial installations or the cable used in conduit installations. It requires both a waterproof jacket, flooded with a jellylike compound to further reduce moisture seepage, and metal armor designed to prevent rodents from gnawing through it.

Cables are typically buried in trenches 18" deep, so they experience less extreme temperature variations than do aerially constructed portions of a system but wider temperature fluctuations than do cables installed in conduits. Thus an intermediate number of amplifiers AGC/ASC is usually required to cover a given distance. However, the cost of appropriately-protected, larger diameter cable exceeds the savings realized by using fewer amplifiers. As a result, the smallest cable to deliver signals of acceptable quality should be used in direct burial installations.

2.3 A DEDICATED COAXIAL CABLE NETWORK DESIGN FOR THE SAINT LOUIS METROPOLITAN AREA

2.3.1 Selection Criteria for Institutions to Receive Network Services

In this section, single and dual cable networks designed to deliver educational services to institutions in the St. Louis area will be described. The institutions which have been chosen are universities and colleges, large industries, and hospitals. These particular types of institutions have been chosen because they are most likely to be interested in improving their staffs' or students' educational opportunities, and they are potentially more able to support the network than are smaller institutions.

Other institutions in the area such as public libraries or elementary and secondary schools might find the network's services attractive, but their inclusion would vastly change the characteristics of the resulting design. For instance, if public libraries were included, the network would have to connect many additional locations that were evenly dispersed throughout the area. This would require installation of much more cable and the cost of the whole network would be greatly increased. Since facilities in branch public libraries probably would receive much less use than facilities in the selected institutions, the actual "per user contact hour" cost of the additional facilities would be increased.

Interconnecting elementary and secondary schools would also require that a large amount of additional cable be installed. Further, as Barnett and Denzau (6) suggest in their consideration of how dedicated networks might be used to interconnect elementary and secondary schools in metropolitan areas, once teachers experience the benefits that the network can offer, the schools might generate enough programming that the network would be used to full capacity. A separate network serving elementary and secondary schools exclusively might be required. While such a separate network could have been included in the network designs presented here, it was felt that this complication would tend to obscure the Chapter's analysis. A similar design, including elementary and secondary schools, could be undertaken using the information presented.

The design presented here interconnects only major institutions with a network requiring only a moderate level of investment. The institutions selected were chosen only for purposes of illustration; the choices made are not based on a market survey. Tables 1, 2 and 3 list the institutions included.

Table 1: Institutions Served In the St. Louis City Area

Universities and Colleges	Location
1. Washington University*	Lindell Blvd. & Skinker Rd. St. Louis
2. Fontbonne College	6800 Wydown Blvd., Clayton
3. Washington University School of Medicine	660 S. Euclid Ave., St. Louis
4. Forest Park Community College	5600 Oakland Ave., St. Louis
5. St. Louis University	221 N. Grand Ave., St. Louis
6. St. Louis University School of Medicine	1402 S. Grand Ave., St. Louis
7. Harris Teachers College	3026 Laclede Ave., St. Louis
Industries	
8. Union Electric	1901 Gratiot, St. Louis
9. Ralston Purina Co.	835 S. 8th St., St. Louis
10. Proctor and Gamble Mfg. Co.	169 E. Grand Ave., St. Louis
Hospitals	
11. Alexian Bros. Hospital	3933 S. Broadway, St. Louis
12. Barnes, Jewish & St. Louis Children's Hospital	Kingshighway and Forest Park Parkway, St. Louis
13. Firmin Desloge Hospital (St. Louis Univ.)	1325 S. Grand, St. Louis
14. Cardinal Glennon Memorial Hospital for Children	1465 S. Grand, St. Louis
15. Chronic Hospital	5700 Arsenal, St. Louis
16. Homer G. Phillips Hospital	2601 Whittier, St. Louis
17. DePaul Hospital	2415 N. Kingshighway, St. Louis
18. St. Luke's Hospital	5535 Delmar Blvd., St. Louis
19. St. Mary's Health Center	6420 Clayton Rd., Richmond Heights
20. Deaconess Hospital	6150 Oakland, St. Louis
21. City Hospital-Starkloff Mem.	1515 Lafayette, St. Louis
22. Cochran Hospital	915 N. Grand, St. Louis

Note: a) This portion of the network includes 23.7 strand miles and 24.7 miles of cable. (Strand miles refers to the length of the route over which cable(s) must be installed; cable miles, on the other hand, refers to the total length of cable installed. Both of these figures are required to estimate construction costs, as construction costs differ over portions of the route where multiple cables have been installed.

---

* Headend.

Table 2: Institutions Served in North St. Louis County

Universities and Colleges	Location
1. Washington University *	Lindell Blvd. & Skinker Rd., St. Louis
2. University of Missouri-St. Louis	8001 Natural Bridge, Bellerive
3. Florissant Valley Community College	3400 Pershall Road, Ferguson
Industries	
4. Emerson Electric Company	8100 W. Florissant Road, Ferguson
5. McDonnell Douglas Corp.	Brown Road, Hazelwood

Note: a) There are no major hospitals in the area.

b) This portion of the network includes 14.4 strand miles and 14.4 miles of cable.

---

* Headend.

Table 3: Institutions Served in South and West St. Louis County

Universities and Colleges	Location
1. Washington University*	Lindell Blvd. & Skinker Rd., St. Louis
2. Webster College	470 E. Lockwood, Webster Groves
3. Meramec Community College	959 S. Geyer Road, Kirkwood
4. Maryville College	13550 Conway Road, Creve Coeur
Industries	
5. Monsanto Company	800 N. Lindbergh Blvd., Creve Coeur
6. Western Electric Co., Inc.	1111 Woods Mill Rd., Ballwin
Hospitals	
7. St. Louis County Hospital	601 S. Brentwood Blvd., Clayton
8. St. Anthony's Medical Center	10006 Kennerly Road., Sappington
9. Shriner's Hospital for Crippled Children	2001 S. Lindbergh Blvd., Frontenac
10. St. Joseph Hospital	525 Couch Ave., Webster Groves
11. St. Luke's Hospital-West	232 Woods Mill Road South, Ballwin
12. St. John's Mercy Medical Center	615 S. New Ballas Rd., Creve Coeur

---

Note: This portion of the network includes 33.9 strand miles and 35.2 miles of cable.

---

* Headend.

2.3.2 Layout of the Network

For ease of illustration, the St. Louis metropolitan areas has been divided into three regions: St. Louis city, north St. Louis County, and south and west St. Louis County.* This division of the metropolitan areas into three distinct regions follows naturally from the location of the institutions that are to be served by the network. By assuming that the network's headend would be located at Washington University, most of the institutions served can be interconnected by a network consisting of five spokes of approximately equal length radiating from the headend. Washington University was chosen as the headend site for convenience; another centralized location would serve equally well.

The institutions within St. Louis city that are to be served by the network are listed in Table 1 and Figure 1 showing the institution's locations and the network's routing. The institutions in north St. Louis County are listed in Table 2 and their locations and the network's routing are shown in Figure 2; south and west St. Louis County institutions are listed in Table 3, and their locations and the cable routing used are shown in Figure 3.

Dividing the network into five independent spokes has several benefits. First, the effective number of channels made available to network users is increased by a factor of five. Specifically, while the number of channels that may be viewed at any particular location served by the network is limited for a single cable network to thirty-five, by dividing the network into five spokes, the total

---

*St. Louis city and St. Louis County are politically autonomous, but cooperate through several intergovernmental agencies.

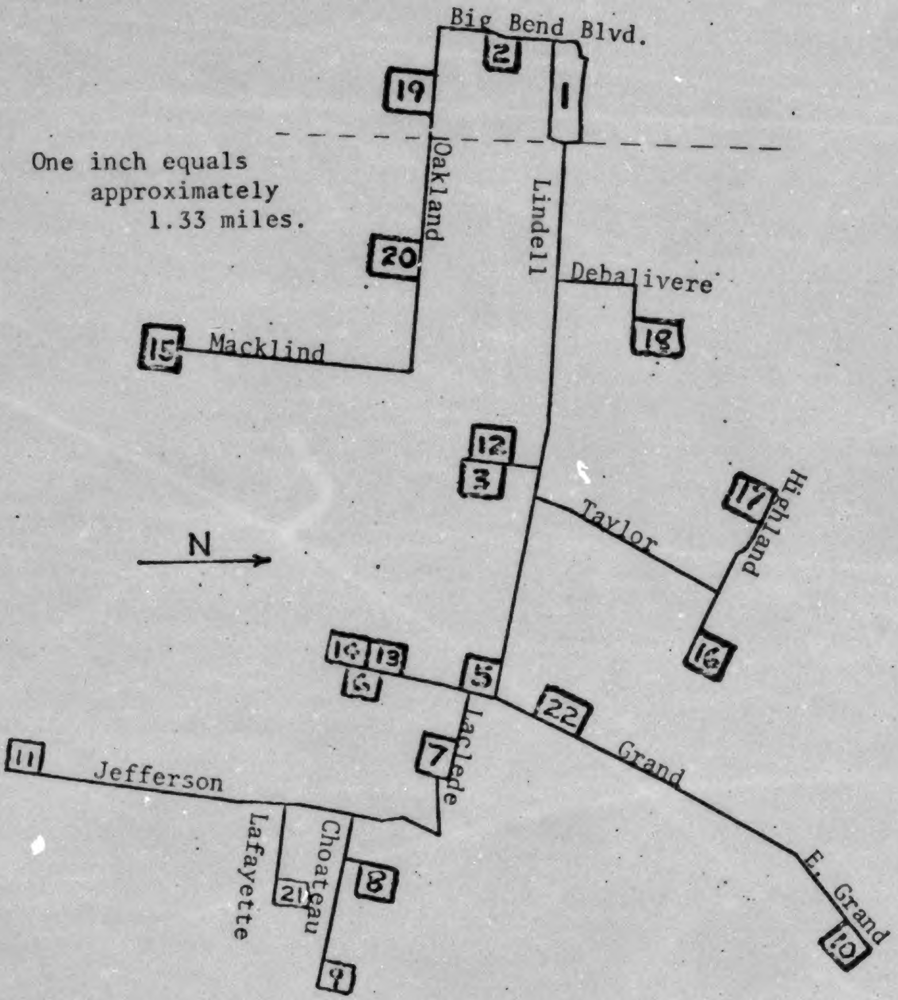
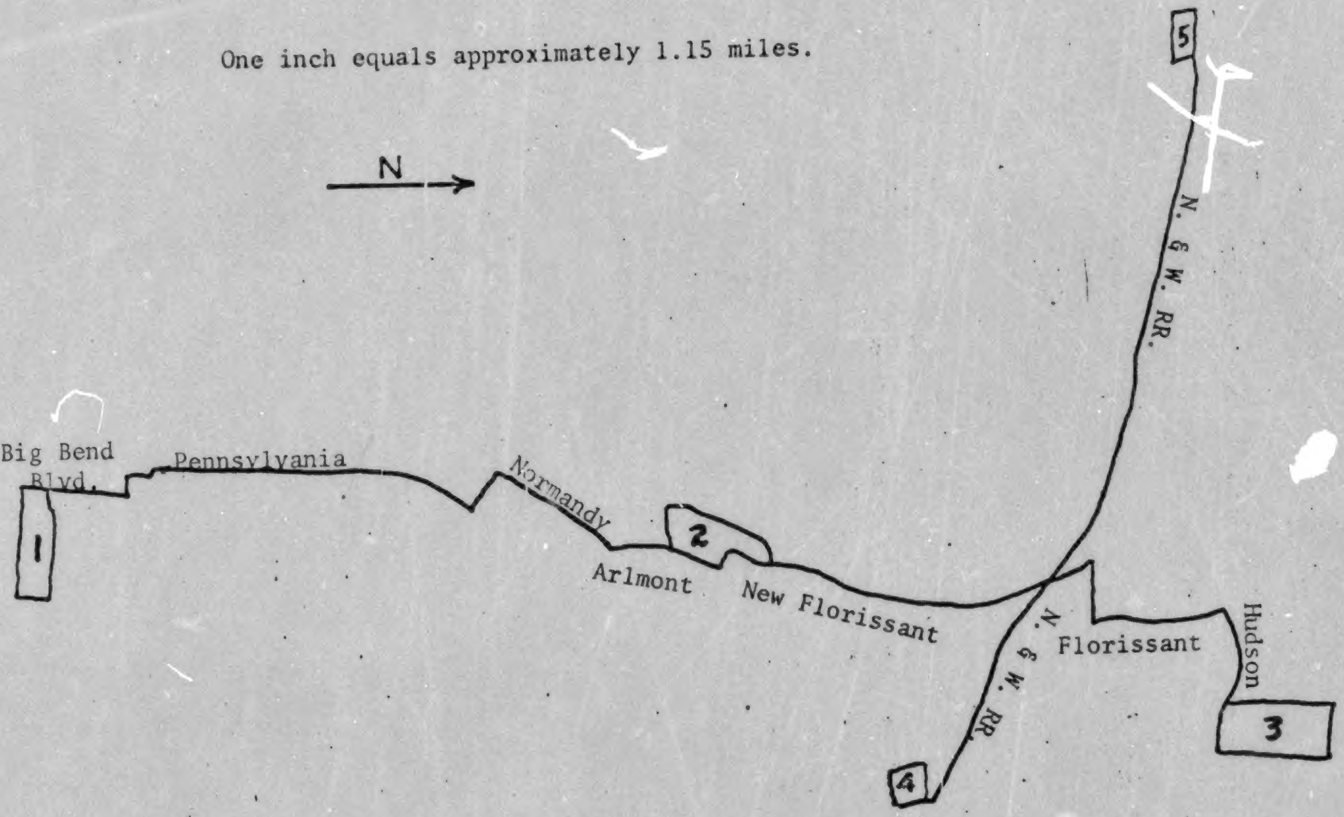

Big Bend Blvd.
2
19
1
One inch equals approximately 1.33 miles.
Oakland
Lindell
20
Debalivere
18
15
Macklind
12
3
17
Highland
Taylor
N
16
14
13
6
5
22
Laclede
7
Grand
11
Jefferson
Lafayette
Choateau
8
21
E. Grand
9
10

Figure 1. Institutions Served in the St. Louis Area


5
N. & W. RR.
N
Big Bend Blvd.
Pennsylvania
Normandy
2
Arlmont
New Florissant
N. & W. RR.
Florissant
Hudson
1
3
4

One inch equals approximately 1.15 miles.

Figure 2. Institutions Served in North St. Louis County

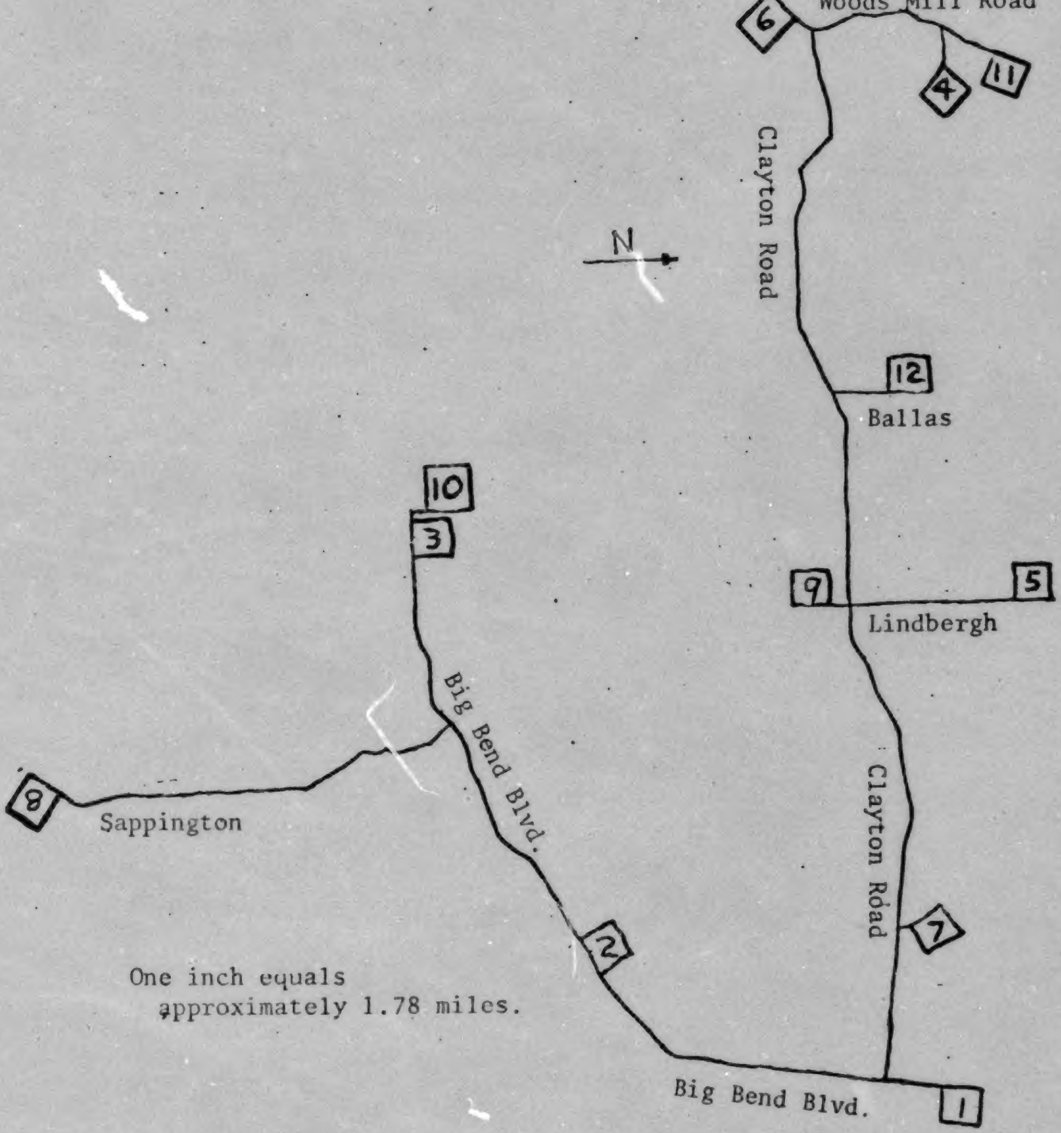

Woods Mill Road
6
4
11
Clayton Road
N
12
Ballas
10
3
9
5
Lindbergh
Big Bend Blvd.
8
Sappington
Clayton Road
7
2
One inch equals approximately 1.78 miles.
Big Bend Blvd.
1

Figure 3. Institutions Served in South and West St. Louis County

number of channels carried on the system is increased to 175, effectively reducing the user density per channel by a factor of five. Similarly, although users at any location served by the network have access to a maximum of only four return video channels, dividing the network into five spokes should reduce the user density per return channel by roughly a factor of five.

Dividing the network into five spokes also reduces the amount of noise that is generated in a spokes' return channels. For instance, if the fourth and fifth spokes were joined where their routes separated at the intersection of Big Bend Blvd. and Clayton Road, (see Figure 3), the cost of installing a second cable from the intersection to the headend would be saved. However, in the return direction the noise generated by the amplifiers in each spoke would be combined, causing increased degradation on signals originated by users and possibly causing so much degradation that signals could no longer be acceptably received at the far ends of the spokes.

Breaking the dedicated networks into five spokes requires that each cable be independently connected to the system headend. Therefore, in some cases several separate cables may have to be run over the same route. For instance three separate cables must run from the headend south along Big Bend Blvd., one each for the network's second, fourth and fifth spokes. (See Figures 1 and 3.) This is one reason why the number of network strand miles and the number of network cable miles are not necessarily equal.

2.3.3 Types of Installation To Be Utilized

Besides being suggested by the locations of the institutions to be served, the division of the St. Louis metropolitan area into three distinct regions is also logical based on the type of cable installation required in each region. Cable in the St. Louis city area is likely to be installed in existing underground conduits owned and utilized by the utilities in most of that area. The only exception is the portion of the network along Big Bend Blvd. and Overland and Macklind Avenues where cable would probably be aerially installed, as utility cables are carried on poles along much of this route. (See Figure 1.)

Relatively few institutions will be served in north St. Louis County which consists mainly of residential communities. (See Figure 2.) Much of the utility cable construction in this region is aerial. However, some of the municipalities have passed ordinances prohibiting aerial construction as an eyesore and other municipalities are expected to do the same, so some of the cable construction in north St. Louis County is underground.

Because the area is not extensively paved, there are few conduits in north St. Louis County and underground cable installation would be by direct burial.

South and west St. Louis County are less densely developed than the rest of the St. Louis area. Utility poles run along most of the cable route. (See Figure 3.) Therefore, the cable in the south and west portions of St. Louis County would be aerially installed.

2.4 COST ESTIMATES FOR A DEDICATED NETWORK DESIGN FOR THE SAINT LOUIS METROPOLITAN AREA

In the previous three sections of this chapter, the technical and topographical factors affecting the design of dedicated cable networks and a possible layout for such a network for the St. Louis metropolitan area were discussed. In this section, the required components for the single and dual cable networks will be listed, and the two networks' costs will be estimated. For a discussion of the specifications and the costs of the components used in designing the networks, the reader is referred to Appendix 5.2.

2.4.1 Cost of the Network

In these networks, video programming originated at any point in the network can be received at any other point in the network with acceptable quality. From an engineering design standpoint, this implies that a signal originated at the far end of one of the network's spokes, propagated through the spoke's return amplifiers, transferred at the headend to a forward cable channel, and then propagated through all of a spoke's forward amplifiers to the spoke's distant end must not be excessively degraded by amplifier noise and distortion. Referring to Appendix 5.1, it can be shown that if .75" styrenefoam coax is used in aerially constructed portions of the network and .5" styrenefoam coax is used in underground (conduit or direct burial installation) portions of the system, video signals are not excessively degraded if all forward amplifiers used have AGC/ASC and every third return amplifier used has AGC.*

The cost estimates include the cost of the cable and amplifiers used and the cost of installing the network. For each area estimates are made for networks installed under two sets of conditions. First if a single cable network is being installed at a time when no other cable construction is being done in the area, and second, if the network's cable is being installed in addition to other cables. The second cost estimate applies for the second cable in a dedicated dual cable network or for each cable in the dedicated network if the network were being installed at the same time as that area was being wired for CATV or such.

---

*The factors affecting the type of coaxial cable resulting in the lowest cost for each of the three types of cable installation are discussed in Section 2.2.2. Interested readers may use the information given in Appendices 5.1 and 5.2 to verify that the cable types used here result in the least expensive networks possible.

A sizeable reduction occurs when installing additional cables aerially because the cost of rearranging existing utility cables on utility poles is charged only to the cost of the first cable installed. Likewise a sizeable reduction in the cost of the second cable is realized using direct burial construction because the cost of the excavating and refilling cable trenches is included only in the cost of the first cable installed. A similar reduction would be realized if the conduits used in the network had to be installed. However, total system cost would be greatly increased over the estimate presented here which assumes use of existing conduits.

Changing from one type of installation to another, each of which uses a different diameter cable with a different interamplifier spacing, could affect where bridger amplifiers should be installed. Using a separate bridger amplifier, rather than a repeater amplifier incorporating bridging facilities, might be appropriate. Similarly, if the bridger amplifier's location was changed, the amount and cost of the multiple cable construction needed to connect the bridger amplifier to the various cable branches would be altered. However, these changes would not significantly affect total system cost.

Table 4 presents the costs for the Saint Louis city portion of the network. The cost of installing a single cable network is approximately $127,000. The cost of an additional cable would be $109,000. Thus the total cost for a dual cable dedicated network installed when no other cable construction is being done is approximately $236,000. If the dual cable network is being installed at the same time that the area is being wired for CATV, the cost of network is approximately $218,000. Each additional cable can be installed simultaneously for 86% of the cost of the first cable installed.

The construction costs of the network serving north St. Louis County are estimated by calculating two sets of cost figures, one for the network assuming all aerial construction, and the other assuming that all underground construction. Each of these network construction costs are then broken down into a per mile cost figure and the estimated cost of the composite network can be determined by adding the cost of the expected percentage of each type of construction to be used.

Table 5 lists the cost estimate for the portion of the network using direct burial installation. The cost of the first cable installed is approximately $141,000, while the cost of each additional cable simultaneously installed is approximately $74,000 (53% of the cost of the first cable installed). Thus, to construct a dual cable network when no other cable installation is being done would cost approximately $215,000; if another cable is also under construction, the dual cable network will cost approximately $148,000.

Table 4: St. Louis City Cable Network Costs
(Re: Figure 1)

Return Video Network--- Aerial and Conduit Installation

For a Single Cable

19.6 miles of .5" Styrenefoam coax with jacket and flooding compound costing $805 per mile	$ 15780
5.1 miles of .75" Styrenefoam coax with jacket costing $1500 per mile	7650
Installation of 18.6 miles of .5" coax in existing conduits costing $1839 per strand mile	34210
Simultaneous installation of 1.0 miles of additional coax costing $1471 per mile	1470
Aerial installation of 5.1 miles coax costing $2870 per mile	14640
12 fwd. AGC/rev. AGC amplifiers costing $1026 per amplifier	12310
34 fwd. AGC/manual rev. amplifiers costing $926 per amplifier	31480
6 fwd. AGC/manual rev. amplifiers with bridging capability costing $1311 per amplifier	7870
Conduit installation of 43 amplifiers costing $29 per amplifier installed	1250
TOTAL COST OF SINGLE CABLE SYSTEM	$126660

For Each Additional Cable Installed Simultaneously

19.6 miles of .5" Styrenefoam coax with jacket and flooding compound costing $805 per mile	$ 15780
5.1 miles of .75" Styrenefoam coax with jacket costing $1500 per mile	7650
Installation of 19.6 miles of coax in existing conduits costing $1471 per mile	28830
Aerial installation of 5.1 miles of coax costing $798 per mile	4070
12 fwd. AGC/rev. AGC amplifiers costing $1026 per amplifier	12310
34 fwd. AGC/manual rev. amplifiers costing $926 per amplifier	31480

Table 4: St. Louis City Cable Network Costs
(Re: Figure 1) (continued)

For Each Additional Cable Installed Simultaneously (cont.)

6 fwd. AGC/manual rev. amplifiers with bridging capability costing $1311 per amplifier	7870
Conduit installation of 43 amplifiers costing $29 per amplifier installed	1250
TOTAL COST FOR EACH ADDITIONAL CABLE	$109240
Total cost for single cable network for St. Louis City equals approximately	$127000
Total cost for dual cable network for St. Louis City equals approximately	$236000

Note: These costs estimates do not include the cost of equipment needed at headend and of equipment needed to connect users to the network. These equipment costs will be estimated in Table 8. Similarly, monthly utility pole and conduit rental fees are not included in the above estimates.

Table 5: North St. Louis County Cable Network Costs
(Re: Figure 2)

Return Video Network --- Direct Burial Construction

For a Single Cable

14.6 miles of .5" Styrenefoam coax with jacket, flooding compound, and armor costing $1214 per mile	$ 17720
14.38 miles of single cable direct burial construction costing $5800 per mile	83400
0.22 miles of additional cable installed simultaneously costing $1348 per mile	300
8 fwd. AGC/rev. AGC amplifiers costing $1206 per amplifier	8210
28 fwd. AGC/manual rev. amplifiers costing $926 per amplifier	25930
1 fwd. AGC/manual rev. amplifier with bridging capabilities costing $1311	1310
37 pedestals installed costing $75 per pedestal including installation	2780
37 amplifiers installed in existing pedestals costing $29 per amplifier installed	1070
TOTAL COST FOR SINGLE CABLE NETWORK	$140720

For Each Additional Cable Installed Simultaneously

14.6 miles of .5" Styrenefoam coax with jacket, flooding compound, and armor costing $1214 per mile	$ 17720
14.6 miles of cable installation in open trench costing $1348 per mile	19680
8 fwd. AGC/rev amplifiers costing $1026 per amplifier	8210
1 fwd. AGC/manual rev. amplifier with bridging capabilities costing $1311	1311
37 amplifiers installed in existing pedestals costing $29 per amplifier installed	1070
TOTAL COST FOR EACH ADDITIONAL CABLE	$ 73920

Table 5: North St. Louis County Cable Network Costs
(Re: Figure 2) (continued)

For Each Additional Cable Installed Simultaneously

Total cost for single cable directly buried network for north St. Louis County equals approximately	$141000
Total cost for dual cable directly buried network for north St. Louis County equals approximately	$215000

Notes: a) Above cost estimates do not include the cost of equipment needed at headend and of equipment needed to connect users to network. These equipment costs will be estimated in Table 8.

b) In direct burial construction, a concrete pedestal is required at each location where amplifiers are to be installed. The pedestals house the amplifiers and allow maintenance to be performed through surface-mounted manhole covers.

On the other hand, the estimates for using aerial installation in north St. Louis County are given in Table 6. The cost of the first cable installed in lieu of other cable construction is approximately $86,000. Additional cables can be installed simultaneously for a cost of approximately $56,000, about 65% of the cost of the first cable installed. If no other aerial cable construction is being done simultaneously, the cost of an aerial dual cable dedicated network serving north St. Louis county would be $143,000; if other cable construction is being done simultaneously, the cost of the dual cable network is approximately $113,000.

For the sake of illustration, assume that one half of north St. Louis County will be wired using direct burial installation, while the other half will use aerial construction. If no other cable construction is occuring, the cost of a single cable dedicated network using both aerial and direct burial construction would be approximately $113,000; if done simultaneously with other cable installation, a single cable network for north St. Louis County would cost approximately $65,000, about 57% of the cost of the single cable network when installed alone. Similarly, a dual cable dedicated network using 50% aerial construction and 50% direct burial construction when no other cable construction was going on, would cost $179,000; if other cable construction was being carried out simultaneously, the cost would be $130,000.

The estimated cost of the portion of the network serving south and west St. Louis County is given in Table 7. Because this portion of the network is made up of two independent spokes, both of which run parallel with spoke 2 from the headend to the intersection of

Table 6: North St. Louis County Cable Network Costs
(Re: Figure 2)

Return Video Network--- All Aerial Construction

For a Single Cable

14.38 miles of .75" jacketed Styrenefoam coax costing $1500 per mile	$ 21570
14.38 miles of single cable construction costing $2870 per mile	41270
7 fwd. AGC/rev. AGC amplifiers costing $1026 per amplifier	7180
16 fwd. AGC/manual rev. amplifiers costing $926 per amplifier	14820
1 fwd. AGC/manual rev. amplifier with bridging capabilities costing $1311	1310
TOTAL COST FOR SINGLE CABLE NETWORK	$ 86150

For Each Additional Cable Installed Simultaneously

14.38 miles of .75" jacketed Styrenefoam coax costing $1500 per mile	$ 21570
14.38 miles of additional cable construction costing $798 per mile	11480
7 fwd. AGC/rev. AGC amplifiers costing $1026 per amplifier	7180
16 fwd. AGC/manual rev. amplifiers costing $926 per amplifier	14820
1 fwd. AGC/manual rev. amplifier with bridging capabilities costing $1311	1310
TOTAL COST FOR EACH ADDITIONAL CABLE	$ 56360
Total cost for single cable aerially installed network for north St. Louis County equals approximately	$ 86000
Total cost for dual cable aerially installed network for north St. Louis county equals approximately	$143000

Notes: a) The above cost estimates do not include the cost of equipment needed at headend and of equipment needed to connect users to network. These equipment costs will be estimated in Table 8.

b) The above costs do not include utility pole rental fee estimated to be $300-$350 per year per strand mile.

Table 7: South and West St. Louis County Cable Network Costs (Re: Figure 3)

Return Video Network--- All Aerial Construction

For a Single Cable	
35,2 miles of .75" jacketed Styrenefoam coax costing $1500 per mile	$ 52800
32.8 miles of single cable construction costing $2870 per mile	94140
2.4 miles of additional cable construction costing $798 per mile	1920
20 fwd. AGC/rev. AGC amplifiers costing $1026 per amplifier	20520
35 fwd. AGC/manual rev. amplifiers costing $926 per amplifier	32410
6 fwd. AGC/manual rev. amplifiers with bridging capabilities costing $1311 per amplifier	7870
TOTAL COST FOR SINGLE CABLE NETWORK	$209660
For Each Additional Cable Installed Simultaneously	
35.2 miles of .75" jacketed Styrenefoam coax costing $1500 per mile	$ 52800
35,2 miles of additional cable construction costing $798 per mile	28090
20 fwd. AGC/rev. AGC amplifiers costing $1026 per amplifier	32410
35 fwd. AGC/manual rev. amplifiers with bridging capabilities costing $1311 per amplifier	7870
TOTAL COST FOR EACH ADDITIONAL CABLE	$141690
Total cost for single cable network for south and west St. Louis County equals approximately	$210000
Total cost for dual cable network for south and west St. Louis County equals approximately	$351000

Notes: a) The above cost estimates do not include the cost of equipment needed at headend and of equipment needed to connect users to network. These equipment costs will be estimated in Table 8.

b) The above costs do not include a utility pole rental fee estimated to be $300-$350 per year per strand mile.

Big Bend Blvd. and Clayton Road, and one of which is parallel with spoke 2 all the way to Oakland Avenue, this estimate includes 2.4 miles of the "additional cable construction" cost in the estimate of the single cable separately installed network. (See Figures 1 and 3.)

The cost of a single cable network constructed in lieu of other cable construction would be approximately $210,000; if done simultaneously with other cable construction, approximately $142,000. The cost of a dual cable network installed alone would be approximately $351,000; if done is simultaneously other cable construction, approximately $283,000.

2.4.2 Costs of Equipment

The cost estimates listed in Tables 4 through 7 consider only the cost of the coaxial cables, the repeater amplifiers, and installation of the cable distribution system. In addition, the costs of the equipment needed at the system headend and at the network users' premises must be considered. The cost of the equipment needed to interface programming sources with the cable network are listed here in Table 8. The headend must have equipment capable of connecting thirty-five channels of programming into the forward channels of each independent cable in the network, as well as equipment for processing the signals on each cable's four return channels. The cost of the equipment interfacing program sources with the cable's forward channels at the headend is approximately $57,000 per cable, or $285,000 for a cable system having five independent cable spokes. The cost per independent cable for the equipment needed to demodulate or change the frequency of signals on each cable's four return channels is approximately $6,700, or $34,000 for a five spoke system.

Table 8: Equipment Required At Headend and On Premises To Interface Programming into Cable Network (9)

For Outgoing Signals On Each Independent Cable At The Headend (35 Channels)

35 video modulators each costing $1225	$ 42880
35 passband filters each costing $ 100	3500
35 channel consoles each costing $ 200	7000
6 six-channel combining networks each costing $105	630
1 signal splitter costing $30	30
1 directional coupler costing $30	30
Equipment installation and checkout	3000
TOTAL OUTGOING SIGNAL EQUIPMENT COST PER INDEPENDENT CABLE	$ 57070

For Incoming Signals On Each Independent Cable At The Headend (4 Channels)

8 passband filters costing $100 each	$ 800
4 signal processors costing $1150 each	4600
4 VHF/VHF converters costing $240 each	960
Equipment installation and checkout (estimated)	380
TOTAL INCOMING SIGNAL EQUIPMENT COST PER INDEPENDENT CABLE	$ 6740

For Each Channel of Programming To Be Originated From User Premises

1 video modulator	$ 1230
1 passband filter	100
1 channel console	200
TOTAL REMOTE SIGNAL ORIGINATION EQUIPMENT COST PER CHANNEL	$ 1530

Note: Because the cost of physically connecting each institution to the cable system is insignificant compared to the total system cost, it will not be considered. Prices given are 1972 prices.

The cost of programming origination equipment, such as the cost of the computer system supplying CAI, and the cost of classrooms suitably equipped to allow remote viewing of lectures will be considered in the next chapter. These costs are dependent on the "services package" used, and therefore do not really constitute part of the cable distribution system.

Finally, the equipment required to interface a video signal originated at a user's premises with one of the network's return channels costs approximately $1500. This estimate does not include the cost of the small diameter cable which normally would be used to connect the user's premises to the network trunk cable, nor does it include the labor costs of the connection. The costs of physically connecting each user to the cable network has been disregarded in the cost estimates presented in this chapter, because the connection costs are insignificant either when compared to the total network cost or when compared to the cost of wiring each building to receive educational services. However, if a CATV network were being designed, due to the large number of users served, these "hookup" charges would be significant. The dedicated networks presented here, on the other hand, only serve forty-one users; as a result, the cost of connecting each institution to the distribution network can be disregarded in the total system cost estimate.

In Table 9, the total cost for the return video dedicated cable network serving the St. Louis metropolitan area is determined. Assumptions made in developing this cost estimate are that the network is being constructed without any other simultaneous network construction, that the portion of the network serving north St. Louis County

Table 9: Estimated Cost of the Cable Distribution Network Serving the St. Louis Metropolitan Area --- Return Video Network

For a Single Cable Network

Cost of network serving St. Louis City area	$127000
Cost of network serving north St. Louis County (50% aerial construction, 50% direct burial construction)	113500
Cost of network serving south and west St. Louis County	210000
Cost of equipment for headend serving five independent cables (see text) for outgoing signals	285000
for incoming signals	34000
Cost of modulators allowing colleges and universities to interface eighteen channels of video programming onto the network costing $1530 per modulator	27500
TOTAL COST FOR SINGLE CABLE DISTRIBUTION NETWORK	$797000

For a Dual Cable Network

Cost of network serving St. Louis city area	$236000
Cost of network serving north St. Louis County (50% aerial construction, 50% direct burial construction)	179000
Cost of network serving south and west St. Louis county	351000
Cost of equipment for headend serving ten independent cables (see text) for outgoing signals	571000
for incoming signals	67000
Cost of equipment allowing users to interface thirty-six channels of video programming onto the network	55000
TOTAL COST FOR DUAL CABLE DISTRIBUTION NETWORK	$1459000

Note: The above costs do not include monthly utility pole and conduit rental fees, nor the cost of connecting each institution into the network. These costs, however do not constitute a significant portion of the total distribution costs.

will be installed using one half direct burial construction and one half aerial construction, and that the universities and colleges served by the network will, in the case of a single cable network, have a total of eighteen modulators capable of interfacing one channel of video programming onto the network and will have a total of thirty-six modulators in the case of a dual cable dedicated network. Under these assumptions, the cost of a single cable dedicated network having video return capabilities is estimated to be $797,000; the cost of a dual cable dedicated network is estimated to be $1,459,000.

3. AN ANALYSIS OF THE SERVICES ABLE TO BE OFFERED ON THE DEDICATED EDUCATIONAL NETWORK

3.1 INTRODUCTION

Chapter 2 discussed the factors affecting the performance of coaxial cable networks to illustrate the types of technical and economic tradeoffs that the designer of educational networks must consider. On the basis of this information a bidirectional dedicated cable network was designed which could be used to deliver educational services to institutions in the St. Louis metropolitan area, and estimated its costs.

This chapter discusses the types and amounts of services that can be delivered over the dedicated coaxial cable networks. All the examples given are based on the single cable return video network option. The capital investment required to implement each service is estimated. In addition, the "per user contact hour" cost of each service is determined, allowing a cost comparison of the different services. These cost estimates indicate that although a versatile nontraditional educational communications system would require a fairly sizeable initial capital investment, the equipment and communications costs of the services per user contact hour are relatively low.

3.2 DETERMINING COMMUNICATIONS COSTS OF THE DEDICATED CABLE NETWORK

The first step in developing cost figures on a "per user contact hour" basis is to determine the cost of the communications channels that will be used to distribute the various network services. We can do this by assuming that each network component has a known useful life and that the capital required to obtain the component is available as a loan at a given rate of interest. Knowing this information, the amount of money that must be paid each year in order that the loan would be completely repaid by the end of the component's useful life can be determined using standard accounting tables. This yearly payment is equivalent to the network component's yearly cost. The component's hourly cost is determined by dividing its yearly cost by the number of hours that the component will be used per year. Similarly, the communications cost per channel hour of a dedicated educational network can be determined by dividing its yearly cost by the product of the number of hours that the network operates per year and the number of network channels.

This approach to determining the communications cost per channel hour largely disregards the effects of inflation; it is felt, however, that the approach is correct for the following reason. Unlike most commercial ventures in which an investor is interested in realizing a profit on his equity after inflation, the nature of the dedicated networks discussed here is such that they would more likely be run on a nonprofit basis. As a result, we need not consider the effects of inflation on equipment costs other than to the extent that inflation affects interest rates. This applies either to capital raised through commercial loans or to capital raised by a bond issue.

Commercial CATV systems are typically assumed to have a twenty year useful life (12); therefore the cost of the dedicated educational network needs to be amortized over twenty years. Electronic equipment, on the other hand, is usually assumed to have a useful life of five years (13); thus, the equipment required at the system headend needs to be amortized over a period of five years. Using these amortization figures, the communication costs per channel hour are determined.

The cost of the single cable network serving the St. Louis city area (refer to Figure 1 and Table 9) if installed independently is $127,000. Assuming that the network's cost is to be repaid over a twenty year period at an interest rate of 8% per year, the yearly cost of the network serving the St. Louis city area is: (14)

$$\text{Cost per year} = \frac{\$127{,}000}{\dfrac{1 - \dfrac{1}{(1 + .08)^{20}}}{.08}} = \$12{,}900 \text{ per year.} \tag{3.1}$$

Similarly, the cost of the equipment needed at the system's headend to interface program sources with a spoke's thirty-five six-MHz forward channels is shown in Table 8 to be $57,000. Amortizing the equipment over a five year period at an interest rate of 8% per year, the yearly cost of the equipment is:

$$\text{Cost per year} = \frac{\$57{,}000}{\dfrac{1 - \dfrac{1}{(1 + .08)^{5}}}{.08}} = \$14{,}300 \text{ per year.} \tag{3.2}$$

The equipment's cost per channel hour can also be determined. Assuming that the educational network is operated eight hours per day, 300 days per year, and recalling the network is capable of carrying up to thirty-five six-MHz forward channels per cable, it can be seen that there are potentially 84,000 forward channel hours available per cable per year. Therefore, the cost of the forward channel interface equipment is given by

$$\text{Cost per channel hour} = \frac{\text{Cost per year}}{\text{Channel hours per year}} = \frac{\$14300}{84000} = \$0.17 \text{ per channel hour} \quad (3.3)$$

The communications costs of the single cable return video network are listed in Table 10.

3.3 TECHNICAL AND ECONOMIC FACTORS AFFECTING THE TYPES OF SERVICES OFFERED ON THE DEDICATED EDUCATIONAL COMMUNICATIONS SYSTEM

This section discusses the technical characteristics determining the quantity of each educational service that might be carried on the dedicated cable network. In addition, the costs of the equipment needed to offer each educational service are outlined and the cost per user contact hour for each of the services is estimated.

3.3.1 Televised Lectures with Interactive Remote Audio Capability

Lectures given at the universities, colleges, and medical schools on the network can be televised for reception at remote locations at other institutions served by the network. By utilizing the return audio channels, students at remote locations can interact with the lecturer, thereby overcoming one of the inherent disadvantages of one way television. Televised lectures can thus make it possible for employed students to continue their educations more conveniently. Further, they can broaden the range of subject matter available to students in traditional academic environments, as well as allowing area educational institutions to share the teaching of basic courses, thus freeing more faculty time for research or increased interaction with students.

Three sets of equipment are required to televise lectures over the network. They include the equipment needed for the studio classroom, for the studio control booth, and for the receiving

Table 10: Per Channel Hour Communication Costs For The Single Cable Return Video Network Serving The St. Louis Metropolitan Area

Area served	Cost per channel hour per spoke	
	Forward Channels	Return Channels
St. Louis City (Re: Figure 1)	23.9¢	24.4¢
North St. Louis County (Re: Figure 2)	29.4¢	29.9¢
South and West St. Louis County (Re: Figure 3)	28.4¢	28.9¢

Notes:

a) The above costs are for a single cable network having return video capability and constructed in lieu of other cable construction.

b) In determining the above costs, it was assumed that the cable plant has a useful life of twenty years, while the headend equipment has a useful life of five years. An interest rate of 8% per year on the network's required capital investment was also assumed.

c) Cost per channel hour refers to the cost of using a six-MHz bandwidth channel in one spoke for one hour. If only a portion of a six-MHz bandwidth channel is required, its cost per hour can be determined by interpolating the costs given above.

d) The cost of the equipment required to allow users to interface with the network's return channels is not included in the costs given above, but will be included in the cost of the equipment required to distribute each type of educational service to be carried on the network.

e) The communications cost estimates given above assume one-hundred percent utilization of the available network bandwidth (thirty-five forward channels and four return channels per network spoke).

classrooms. The components of each of these sets will be described below, as will the role of the headend of the network in providing this service.

For studio classrooms, several television cameras are typically used. One camera located at the rear of the classroom televises the lecturer and any notes that are written on the blackboard, while another camera mounted on the ceiling above the lectern allows students to view written materials displayed on the lectern. A third camera may be positioned behind the lecturer to pick up the audience. In addition, the studio classroom must have audio facilities both for the lecturer and to allow remote students to hear the questions of students sitting in the studio classroom and vice versa. Finally, television monitors are needed so that the lecturer can observe the televised presentation and students in the studio classroom can observe on monitors any written materials or visual aids such as films or video tapes that the lecturer includes in the televised presentation. Experience with similar studio classrooms in typical university instructional television systems using Instructional Television Fixed Service (ITFS) transmission has indicated that the average cost in 1971 prices* for the equipment in a studio classroom is $23,000. (15)

Each studio classroom requires a studio control booth from which the television cameras can be operated, films and tapes can be shown, and special effects can be arranged. Special effects might include split-screen views simultaneously showing the lecturer and a visual aid. A typical studio control booth for a university instructional television system cost $19,000 per classroom. (15) In an ITFS instructional television system, programming from the studio booth typically is routed to a master control center where the programming is transmitted throughout the system. However, in a dedicated cable network, the master control function is accomplished at the cable system's headend. As a result, a modulator is required in studio control booths distributing programming on a coaxial cable network to allow video lectures to be interfaced with the network's return channels. Therefore, we estimate that the total cost of the equipment required in a studio classroom's control booth is $20,500.

---

*All prices in Section 3.3.1 date from 1971 unless otherwise specified.

The receiving classrooms require several different types of equipment to allow remotely located students to view the televised lecturers and to interact with the lecturer. First, each receiving classroom must have at least one television monitor. However, experience with instructional television systems has shown that one monitor for each group of eight students seated facing the monitor in two rows of four behind tables is an optimal arrangement. In addition, equipment allowing the remote students to interact with the lecturer is required.

An example of suitable equipment with interactive audio capability is the terminal designed for use with the Vicom Manufacturing Company's Queset interactive cable television system. (16) These terminals perform several functions. They contain a 26-channel converter which allows standard VHF television sets to receive cable channels having nonstandard frequency assignments, and each terminal's keyboard and internal character generator allow alphanumeric messages to be sent or received from any terminal in the system. In addition, each terminal contains an audio modulator that can be activated from the cable system's headend, allowing lecturers to control the times during the lecture in which questions from remote students are answered.

Terminals similar in function to Vicom's Queset terminals but modified to allow several microphones to be used per terminal are suitable for use in receiving classrooms. An estimate of the cost of the modified Queset terminal is $230, while an estimate of the cost of the monitor and the furniture required in each eight person receiving classroom module is $965.

A minicomputer system is required at the network headend to allow polling of the module terminals and to indicate to lecturers at which terminal students have a question, so that the appropriate terminal's modulator can be activated. The price of a polling system capable of serving up to 10,000 terminals is $45,000 for the computer system plus $15,000 for the required software. (16) If no more than several hundred terminals were required in the televised lecture service, the polling function could probably be accomplished on the same computer used to provide computer aided instruction. Therefore the cost of a separate polling system has not been included in the estimate of cost of the equipment required to provide televised lecture interactive service presented here.

Finally, the cost of operating the televised lecture service should be considered. The cost of operating a university instructional television system using an ITFS transmission network for program distribution varies from thirty dollars per program hour in a four channel system; the reduction in cost can be attributed to economies of scale. (15) The operating costs of providing televised lectures over a dedicated cable network would differ from those of a system using ITFS transmission in two ways. First, the number of lectures that could be simultaneously carried on a dedicated cable network would be much larger than an ITFS network's maximum of four channels; as a result, one could expect that further economies of scale could be realized with a cable network. On the other hand, all of the studio classrooms in the ITFS instructional television systems are located together, while the studio classrooms serving users of a dedicated cable network would be located at the individual colleges, universities, and medical schools served by the network. Therefore, negative economies of scale might be experienced as the number of program origination points increased. Considering both of these factors, we assume that the cost of providing televised lectures to cable system users is seventeen dollars per program hour, regardless of the number of lectures that can be simultaneously carried by the cable system.

To determine the amount of televised lectures services that can be offered, the service's cable bandwidth requirements must be examined. If a studio classroom is not at the cable system's headend, one return channel in its own spoke is needed to transmit a televised lecture to the headend for distribution. From the headend, each televised lecture requires one forward channel and one twenty-kHz return audio channel per spoke on which it is to be received. Further, to poll the receiving classroom terminals for questions from students, forward and return bandwidth are required in each of the network's spokes for digital data transmission.

Thus the number of televised lectures that the network can carry is limited by the amount of available return bandwidth on the network. Each cable has twenty-five MHz of return bandwidth, allowing up to four lectures per spoke to be simultaneously originated. We assume in the services packages designed here, however, that no more than three lectures are originated simultaneously from remotely located classrooms on any cable spoke. These three lectures require the use of eighteen MHz of return cable bandwidth; the remaining seven MHz of return cable bandwidth is required to allow the other network interactive services to be offered.

Under these assumptions, a maximum of fifteen lectures originated from studio classrooms remotely located from the system headend can be simultaneously carried on the network. The educational institutions from which the lectures might originate however, are not evenly dispersed throughout the network. Because of this, in some cable spokes institutions will be required to share the available return channels, while in other spokes, all of the available return channels would not be used. Since lectures originated at the cable system's headend do not require the use of return cable bandwidth for transmission, the total number of lectures originated from there is limited only by the forward channels available in the network's five spokes. Thus, the amount of services which can be offered on the network depends upon both the bandwidth available and the locations of the institutions using the network.

Assume that 18 studio classrooms located as follows: two studio classrooms at each of the three universities served by the network; two classrooms at each of the three community colleges served by the network; one classroom at each of the two medical schools served by the network; and one classroom at each of the network's four liberal art colleges. These assignments are made partly to equalize the number of studio classrooms per spoke and partly in anticipation of the amount of programming which might originate from each of the educational institutions considered. If these classroom locations are used, the five studio classrooms at institutions served by cable spoke number one (Figure 1) share the spoke's three available return channels. Each of the three classrooms served by spoke number two (Figure 1) has the use of its own dedicated return channel, while the four classrooms served by the cable network's third spoke (Figure 2) share its three available return channels. Only one studio classroom is located on spoke four (Figure 3), while each of the three studio classrooms located on spoke five (Figure 3) has the use of its own dedicated return channel. Because the network design assumes that the system headend would be located at Washington University, the two studio classrooms located there would not require any of the network's return channels; they would be connected directly to the cable system's headend.

It can be seen that the eighteen studio classrooms can simultaneously originate up to fifteen lectures, requiring fifteen forward channels and fifteen twenty-kHz bandwidth return audio channels per spoke. A total of thirteen return video channels is required to carry programming from remote studio classrooms to the headend, and 125 kHz of bandwidth is required in both the forward and return bandwidth of each cable spoke to allow polling of the receiving classroom terminals. With this information, and using the per channel hour communication costs listed in Table 10, the hourly communication cost of providing televised lectures with interactive audio capability is summarized below:

Communications Requirements of Televised Lectures

Spoke number	1	2	3	4	5
Forward channels required*	15.02	15.02	15.02	15.02	15.02
Return channels required*	3.07	3.07	3.07	1.07	3.07
Hourly cost of required forward channels	$3.59	$3.59	$4.41	$4.27	$4.27
Hourly cost of required return channels	$0.75	$0.75	$0.92	$0.31	$0.89

From the above figures, it can be seen that the per system hour forward communications cost of distributing televised lectures is $20.13; while the per system hour return communications cost is $3.62; the total communications cost of distributing televised lectures with return audio capability is $23.75 per system hour.

To determine the costs of televised lectures per user contact hour, the number of students that will be able to view the lecture must be estimated. Assume that the three universities and the three community colleges served by the network each have receiving facilities for 128 students, while the four colleges and two medical schools served by the network each have receiving facilities for 64 students. In addition, assume the twenty-nine hospitals and industries served by the network are receiving facilities for sixteen students each. Thus, up to 1616 students could view the fifteen lectures simultaneously distributed over the dedicated educational network, and the cost per user contact hour would be 23.6¢.

---

*Channels as used here refers to six-MHz bandwidth video channels. Fractions of channels required refer to the required bandwidth of audio and digital signal transmission services.

Using amortization assumptions similar to those used in determining per channel hour communication costs, the cost of providing televised lectures with interactive audio capabilities is outlined in Table 11.

3.3.2 Central Refresh TICCIT CAI Services

In this service, a TICCIT system similar to the interactive television system proposed by the MITRE Corporation to provide services to cable television subscribers (12, 17) allows computer aided instruction to be received at terminals located at the institutions served by the network. Modes of instruction include computer generated displays, computer selected audio, and computer selected videotapes. While the MITRE interactive television system was designed to serve up to 1000 home terminals on a time sharing basis, the dedicated cable system designed for St. Louis would serve up to ninety dedicated terminals full time. (This assumes that the ninety terminals would receive enough use to warrant assigning one cable channel exclusively to one terminal. If the terminals did not receive full time use, additional terminals could be added to the system to take advantage of the spare computer and channel capacity available.) The centrally refreshed system allows videotapes to be included as a part of the instruction mix. If videotapes are not be used, the remotely refreshed TICCIT system described

Table 11: The Estimated Cost of Providing Televised Lectures

Cost of equipment for 18 studio classrooms	$414,000
Cost of equipment for 18 studio control booths	369,000
Cost of 202 receiving classroom modules accommodating 1616 students	195,000
TOTAL CAPITAL INVESTMENT REQUIRED	$978,000
Total equipment cost per system operating hour*	$102.05
Total communication cost per system operating hour	23.75
Total support cost per system operating hour**	255.00
TOTAL COST OF TELEVISED LECTURE SERVICE PER SYSTEM OPERATING HOUR	$380.00

Communication cost per student contact hour equals 1.5¢

Total cost of service per student contact hour equals 23.6¢

---

*Equipment amortized over five years, with 2400 hours of operation per year. An interest rate of eight percent per year has been assumed.

**15 channels at $17.00 per program hour.

in section 3.3.3 allows TICCIT CAI services to be supplied without requiring one forward cable channel per terminal.

The equipment costs of the proposed interactive television system are given in Table 11 of our previous report (1), which is repeated on the following page for convenience. Of the listed equipment, the telephone parts and the trailer which would contain the TICCIT computer system are not required in a system serving users of the dedicated network. In addition, 1000 home terminals would not be required; required instead are the ninety dedicated terminals which each require a color television receiver, a converter for receiving cable channels having nonstandard frequency assignments, a keyboard and associated digital circuitry. Assuming suitable television receivers can be bought for $350, that converters cost $50 each, and that the TICCIT keyboard and electronics cost $400, each terminals served by centrally refreshed TICCIT system would cost $800.

The MITRE Corporation estimates that the cost of operating the proposed interactive television system for three years is $463,000, exclusive of the salaries required for personnel to evaluate the experimental system's effectiveness and act as liasons with community organizations, and for their travel expenses during the three year experiment. (17) We will therefore estimate that the yearly cost of operating a TICCIT system is one-third of that, or approximately $154.000.

Because centrally refreshed TICCIT terminals require the full time use of a forward cable channel, the number of terminals that can be assigned to any particular institution depends upon how many

TICCIT System Equipment Costs (1)
(1974)

Computing System	$229,825
Video System, Audio and Video Interface	381,660
Home terminals (1000)	400,000
Analog Storage	20,000
Spares	30,000
Test Equipment	20,000
Computing Supplies (Tapes, Discs, and Paper)	16,000
Telephone Parts*	10,000
Trailer, shielded with air conditioning and raised floor	40,000
Total	$1,147,485

---

*Equipment is used to establish a telephone data link from the Stockton TICCIT system to the Mitre Corporation's headquarters in Virginia.

institutions are to be served on a particular cable spoke and how much forward cable bandwidth is available. For example, if we assume that the central refresh TICCIT system's ninety terminals are distributed evenly among the forty-one institutions served by the network, each institution has the use of approximately two centrally refreshed TICCIT terminals. This requires that forty dedicated channels be available to serve the twenty institutions located on spoke one (Figure 1), while only eight channels are required to serve the four institutions located on spoke three (Figure 2). Since each spoke has only thirty-five forward channels, and since some of these are required for other services, it is obvious that all of the institutions in the system cannot receive the same amount of centrally refreshed TICCIT services. For similar reasons, all participating institutions of a similar type (e.g., industries or hospitals) could not receive equal amounts of centrally refreshed TICCIT services. Thus, the amount of service an institution can receive depends on the number of users to be served on its spoke.

To estimate the communication costs of operating the centrally refreshed TICCIT system, the terminal density per system spoke must be determined. Assuming that fifteen forward channels will be required per spoke to distribute televised lectures and that two channels will be required to carry digital signals, a maximum of 18 channels per spoke are available to distribute centrally refreshed TICCIT services.

Given 18 available channels per spoke, the following terminal placement has been assumed. In spoke one (Figure 1), St. Louis University could have two terminals, while the thirteen hospitals and other three educational institutions (excluding Washington University at the system headend) could each receive one centrally refreshed TICCIT terminal. Centrally refreshed TICCIT services would not be available to the three industries served by spoke one as the eighteen available channels are required to serve the educational institutions and hospitals. On spoke two (Figure 1) each of the two colleges would use six TICCIT terminals, while the three hospitals receive one terminal each, requiring a total of fifteen forward channels. On spoke three (Figure 2), the two educational institutions served could receive six terminals each, with two terminals alloted to each of the two industries, requiring sixteen forward channels. On the fourth spoke (Figure 3) the one college would be alloted six terminals, while the four hospitals and two industries served would each be alloted two terminals, requiring the full eighteen channels. On the fifth spoke (Figure 3), the two educational institutions would each be alloted six TICCIT terminals, while the hospitals would be alloted two terminals each, requiring sixteen forward channels. The above terminal assignments account for eighty-three of the ninety terminals that the system can support. The remaining seven terminals would be at Washington University which being at the system headend, would not require the use of any of the network's forward channels.

The above terminal assignments are only suggestions. A different set of terminal assignments might be chosen depending on the needs of the institutions involved. If many of the institutions did not require full time use of the centrally refreshed TICCIT services, additional terminals could be added in the network to use the available channel and computer capacity through sharing.

To allow polling of the ninety centrally refreshed TICCIT terminals, 225 kHz equivalent bandwidth is required in each spoke's forward and reverse bandwidth. In stating bandwidth requirements in terms of equivalent bandwidth, the information bandwidth, rather than the actual bandwidth required to operate the system, is stressed. More specifically, consider the following example. MITRE's proposed interactive television system used 2.5 MHz channels in each spoke's forward and return bandwidths in order to poll 1000 user terminals. The system for use in the dedicated educational system, on the other hand, has only 90 terminals and therefore, requires an equivalent bandwidth 90/1000 that of the 1000 terminal system. By expressing digital signal bandwidths in terms of equivalent bandwidths, the total bandwidth required for a polling system addressing several types of different terminals can be easily computed. If only one kind of service were to be offered, on the other hand, the actual bandwidth used by the polling system would be a better measure of the required bandwidth.

The channel requirements per spoke and, referring to Table 10, the communications costs associated with operating the centrally refreshed TICCIT CAI system on the St. Louis dedicated network are summarized below.

Communication Requirements of Central Refresh TICCIT Services

Spoke number	1	2	3	4	5
Forward channels required*	18.04	15.04	16.04	18.04	16.04

---

*Channels refers to 6 MHz bandwidth television channels. Fractions refer equivalent bandwidths required for digital polling of terminals.

Return channels required*	0.04	0.04	0.04	0.04	0.04
Hourly costs of required forward channels	$4.31	$3.59	$4.72	$5.12	$4.56
Hourly costs of required return channels	1.0¢	1.0¢	1.2¢	1.2¢	1.2¢

The hourly communication cost of running the system is equal to $22.36. Assuming a ninety terminal system, the resulting communication cost per user contact hour is twenty-five cents. Assuming that the required TICCIT equipment will be amortized over five years at an interest rate of 8% per year, the total cost of providing centrally refreshed TICCIT services is summarized in Table 12.

3.3.3 Remote Refresh TICCIT CAI Services

The centrally refreshed TICCIT system described in the previous section, requires the use of one channel per terminal so that the instruction mix offered could include computer selected videotapes. With this large bandwidth requirement, the proposed single cable dedicated network is limited to one centrally refreshed TICCIT system, servicing ninety terminals, not a significant number. The number of channels required to operate the TICCIT system can be decreased by installing video refresh memories (frame grabbers) at the terminals instead of the headend. Then only one channel per spoke is required to operate the TICCIT system. Each computer generated frame is sent to a terminal only once, where the terminal's television display is refreshed by its internal video refresh memory. Thus, each new frame generated requires the use of the network forward channel only for one-sixtieth of a second; up to

---

*Channels refers to 6 MHz bandwidth television channels. Fractions refer equivalent bandwidths required for digital polling of terminals.

Table 12: The Estimated Cost of Providing Central Refresh TICCIT Services

Central Refresh TICCIT Equipment Costs	
Computing system	$230,000
Video System, Video and Audio Interface	382,000
90 Central Refresh TICCIT Terminals	72,000
Analog Storage	20,000
Spares	35,000
Test equipment	20,000
Computing Supplies	16,000
TOTAL CAPITAL INVESTMENT REQUIRED	$775,000
Total equipment cost per system operating hour*	$80.87
Total communication cost per system operating hour	22.36
Total support cost per system operating hour**	64.38
TOTAL COST OF CENTRAL REFRESH TICCIT SERVICES PER SYSTEM OPERATING HOUR+	$167.61

Communication cost per student contact hour equals 25¢

Total cost of service per student contact hour equals $1.86

---

*Equipment amortized over five years, with 2400 hours of operation per year. An interest rate of eight percent per year has been assumed.

**2400 hours of system operation yearly assumed.

+This figure does not include the cost of developing courseware for the system. Courseware development costs have been estimated as $375,000 per subject per semester. (18) Were TICCIT systems to become more widely used, however, standard courseware packages would probably be offered at a much reduced price.

3600 computer generated frames could be transmitted per second by one forward cable channel. Of course, because the channel is time shared by all of the remotely refreshed TICCIT terminals, videotapes requiring an entire channel for distribution can no longer be received. However by reserving several voice channels on the cable's forward bandwidth and incorporating computer controlled FM receivers into the remotely refreshed TICCIT terminals, computer selected audio messages can still be included in the TICCIT courseware's instruction mix.

The equipment required for a remotely refreshed TICCIT system differs from that of a centrally refreshed TICCIT system in two ways. First, in addition to the color television, converter, and TICCIT keyboard and digital electronics included in the terminals of the centrally refreshed systems, the terminals of the remotely refreshed TICCIT system also include a video refresh memory and a computer controlled FM receiver allowing computer selected audio to be received. MITRE estimates the 1973 cost of a digital video frame grabber producing saturated color displays with no "grey" scale as being $875. (19) Similarly, the cost of the remotely controlled FM receiver is estimated as being $150. The addition of this equipment raises the equipment cost per remote refresh terminal to $1825.

The second difference in the equipment required for a remotely refreshed system is that the complex video system of the centrally refreshed TICCIT system (which included twenty computer controlled video tape recorders) is not required. The centrally refreshed system required a video switching frame capable of interfacing the computer system's ninety output channels with the cable system.

The remotely refreshed system, on the other hand, requires a switching frame that will interface the computer's single video output channel (which is composed of single frames that are selected and stored at the appropriate terminals) and twenty audio output channels onto the five spokes of the cable system. MITRE estimates the cost of this simplified video system, which no longer includes twenty video tape recorders, to be $18,000. The reduction in video system costs from $382,000 for the central refresh TICCIT system to $18,000 for the remote refresh TICCIT system compensates for the higher cost of the remote refresh terminals.

The remotely refreshed TICCIT system requires partial use of one forward channel per network spoke, plus 400 kHz bandwidth for twenty channels of audio programming and a 225 kHz equivalent bandwidth for digital polling in each spoke's forward channels. 225 kHz equivalent bandwidth is required in each network spoke's return bandwidth to allow terminal-to-headend communication. Referring to Table 10, the hourly cost of 1.1 forward channels per spoke is $1.47; the hourly cost of 0.04 return channels per spoke is 5.5 cents. Therefore, the hourly communication cost of operating one remote refresh TICCIT system is $1.53; assuming a ninety terminal system, the communication cost per student contact hour is 1.7¢.

Finally, we have assumed that the yearly support costs for the remote refresh TICCIT system are the same as the yearly support costs for the central refresh TICCIT system, $154,500. Assuming that the equipment required for the remotely refreshed TICCIT system will be amortized over a five year period at an interest rate of eight percent per year, the total cost of providing remote refreshed

TICCIT CAI services is summarized in Table 13.

Since a single remote refresh TICCIT system does not use the six MHz bandwidth forward channel to its full capacity, several remote refresh TICCIT systems could share the forward cable channel. For example, assuming that each TICCIT terminal requires three new frames to be generated per minute, each TICCIT computer system serving ninety terminals generates only 270 frames per minute. The forward video channel, on the other hand, can distribute up to 3600 frames per minute; thus, the channel utilization per ninety terminal TICCIT system is 7.5 percent. If eight TICCIT systems were to use the same channel to distribute TICCIT still frames, assuming that a scheduling arrangement among the systems was made so that transmissions from the different systems did not overlap, then the forward channel would still only have 60 percent utilization. Each of the eight systems would require the use of the 6 MHz forward channel only 7.5 percent of the time. In addition, each remote refresh TICCIT system would require 0.1 forward channel per spoke and 0.04 return channel per spoke for a total of 0.225 forward and 0.04 return channels required per spoke per system.

With eight remote refresh TICCIT systems sharing one channel the hourly communication cost for each system would be 35.6 cents and, referring to Table 13, the total hourly cost of operating each of the eight remote refresh TICCIT systems would be $115.14. Thus, 720 remote refresh TICCIT terminals could be serviced at a per student contact hour cost of $1.28. Additional economies of scale might be realized by using one large terminal processor rather than eight small TICCIT terminal processors to handle communications

Table 13: The Estimated Cost of Providing Remote Refresh TICCIT Services

Remote Refresh TICCIT Equipment Costs	
Computing System	$230,000
90 Remote Refresh TICCIT Terminals	164,000
Video System	18,000
Spares	35,000
Test Equipment	20,000
Computing Supplies	16,000
TOTAL CAPITAL INVESTMENT REQUIRED	$483,000
Total equipment cost per system operating hour*	$ 50.40
Total communication cost per system operating hour	1.53
Total support cost per system operating hour**	64.38
TOTAL COST OF REMOTE REFRESH TICCIT SERVICES PER SYSTEM OPERATING HOUR⁺	$116.31

Communication cost per student contact hour equals 1.7¢

Total cost of service per student contact hour equals $1.29

---

*Equipment amortized over five years, with 2400 hours of operation per year. An interest rate of eight percent per year has been assumed.

**2400 hours of yearly system operation assumed.

⁺This figure does not include the cost of developing courseware for the system. Courseware development costs have been estimated as $375,000 per subject per semester. (18) Were TICCIT systems to become more widely used, however, standard courseware packages would probably be offered at a much reduced price.

scheduling for the eight TICCIT computer systems.

3.3.4 Community Information Services

In the previous analyses of services given in this chapter, we have assumed that the network would only be used during business hours (i.e., 8 hours per day, 300 days per year) and that it would be used only by people directly connected with the institutions served by the network. But given the after hours availability of the equipment, it would be possible to allow the public to use network facilities in the evenings either as a good will gesture or for a small fee. One service that might be provided is to use an existing computer-aided instruction system to allow the public access to a package of community information material similar to that suggested for use on MITRE's proposed interactive television system. (12) We have assumed that in providing these services, no charge would be made for the cost of using the CAI equipment. Since the CAI system would be built primarily to serve student users connected with the institutions participating in the network, and the amount of public use after hours would probably be much less than during normal business hours, it was felt that equipment amortization costs should be included only during periods of institutional use.

Under these assumptions, community information services could be offered for the price of the system's communication costs, plus the cost of operating the system during the evenings. In addition, the cost of developing the community information package that was to be available on the computer system would have to be included. However, the development of the information package might be undertaken by agencies of local government or community organizations. In that case, its effect on system cost could be disregarded.

As an example of the cost of providing community information services, consider the cost of implementing such a service after hours on a remote refresh TICCIT system. Referring to Table 13, the system's total communication cost per system operating hour is $1.53, while the hourly system support costs are $64.38. Thus the hourly cost of providing community information services is $6[illegible].91; this corresponds to a per user contact hour cost of $0.73.

3.3.5 PLATO IV Computer Aided Instruction Services

The University of Illinois' PLATO IV system employs a large central computer and innovative display technology to provide versatile computer aided instruction to large numbers of terminals. The PLATO system was designed to serve up to 4032 terminals. However, user characteristics have placed a heavier than anticipated load upon the central computer facility of the present developmental system, and it is able only to serve 1008 terminals. In this section, we estimate the cost of offering PLATO IV services to users of the St. Louis dedicated cable network assuming the system has either a 1008 or 4032 terminal capacity. The actual number of terminals an operational PLATO system is capable of supporting and the resulting costs of instruction probably lie between these two estimates.

A large general purpose computer able to meet the requirements of the PLATO IV system costs approximately 4.5 million dollars; 2.5 million dollars for the mainframe of the computer and 2 million dollars for the two million words of memory and the input/output equipment required. An estimate for the system software, including some course development programming, is an additional 1.5 million dollars. If the PLATO system is to be used on a broadband network such as the proposed dedicated cable network, a Network Interface Unit (NIU) is required to form the data from the PLATO central computer into a signal that is compatible with standard broadcast television equipment. Assuming that the system can support 1008 terminals, one NIU would be required to form data for the 1008 terminals into a single signal that is carried on one forward channel in each of the cable network's five spokes. Assuming the system could support 4032 terminals, four NIU's and four channels per network spoke are required. The estimated cost of an NIU is $30,000. (20)

Each PLATO IV terminal consists of a plasma panel with random-access image selector, a keyboard, and a controller whose outputs can control the optional random-access audio system or other hardware. These terminals should be able to be produced within the cost limits of $1500 to $3000 each, depending upon quantities produced and optional accessories provided. (21) Current production costs of a PLATO terminal having random-access audio capacity, however, are estimated to be $5,500 for terminals produced in 4000 terminal quantities. (22) Therefore, we assume that the cost of terminals used to deliver PLATO services to users of the St. Louis dedicated cable network is $5,500.

To fully utilize the PLATO system's 4000 terminal expected capacity, the PLATO terminals can be serviced over voice-grade (3kHz bandwidth) telephone lines. This allows PLATO services to be delivered in rural areas not having broadband communication facilities. Because the terminals are designed to be used with telephone lines, rather than by time-sharing a broadband communications channel, a means of extracting a particular terminal's data from the composite output data transmitted on a cable channel by an NIU is required. A PLATO IV site controller is therefore used to extract the data for up to thirty-two terminals from the composite data signal. In addition, the site controller concentrates the return data from up to thirty-two terminals into a single low data rate (4800 bits per second) 3 kHz bandwidth signal. For a 1008 terminal system, the return data rates to the computer from the system terminals would total 151.2 kilobits per second, requiring a return bandwidth per cable spoke of approximately 300 kHz. Similarly, for a system capable of supporting 4032 terminals, a return bandwidth of approximately 1.2 MHz is required. The estimated cost of a PLATO IV site controller is $9,000. (20)

One site controller is required at each location receiving PLATO CAI services via the dedicated cable network. Therefore, the cost of the site controllers required to deliver PLATO services depends upon the distribution of PLATO terminals throughout the network. Any location having from one to thirty-two terminals requires its own site controllers. If more than thirty-two terminals are used in one location, a separate site controller will be required for each thirty-two terminals or fraction thereof.

In order to estimate the number of site controllers required, we assumed that for the 1008 terminal system, terminals would be located as follows: 96 terminals at each of the three universities and three community colleges served by the system, requiring a total of eighteen site controllers at the six institutions; 48 terminals at each of the two medical schools and four colleges served by the network, requiring a total of twelve site controllers to service the four colleges and two medical schools; eight terminals at each of the seven industries and four terminals at each of the twenty-two hospitals served by the network, requiring a total of twenty-nine site controllers to service terminals at the hospitals and industries served by the network. Thus, a total of fifty-nine site controllers are required to interface the 1008 PLATO terminals with the dedicated cable system. If the PLATO system used on the network is assumed to be able to support 4032 terminals, a similar allocation of PLATO terminals can be made by assuming that the terminal allocation made at each institution in the 1008 terminal system is increased by a factor of four. Interfacing 4032 PLATO terminals with the cable system requires the use of 137 site controllers. Some economies of scale in site controllers are realized in the 4032 terminal system.

Previous experience with large scale computer systems has shown that the cost of operating a large scale computer is approximately equal to the cost of the computer itself. (23) Therefore, we assume that for both the 1008 terminal PLATO system and the 4032 terminal PLATO system that the yearly operation cost of each system is equal to one-fiftn of the cost of the PLATO central computing facility plus one-fifth the cost of the required Network Interface Units. Assuming that the required equipment is amortized over a five year period at an annual interest rate of eight percent, the costs of a 1008 terminal PLATO IV CAI system are summarized in Table 14; similarly, the costs of a 4032 terminal PLATO system are summarized in Table 15.

3.3.6 Distribution of Prerecorded Videotapes

Another service that might be made available over the dedicated cable network is the distribution of prerecorded videotapes. Using this service, students who had missed or wanted to review a televised, interactive lecture could request that a videotape of the lecture be played over the system. Similarly, prerecorded visual aids and company training tapes could be distributed over the system. Tapes might be shown on a scheduled basis, as is done presently on broadcast television, or viewers could use the cabel system's return channels to request that a particular tape be shown. The cost estimates given here assume that users request particular tapes using the return audio communication capabilities of existing classroom modules used for receiving televised lectures. Since these classroom modules would chiefly be used for receiving live televised lectures, rather than prerecorded videotapes, no charge for the use of the receiving classroom modules is included in our estimates of the cost of providing videotape distribution services.

In their examination of the costs of dedicated communication networks to be used by primary and elementary schools, Barnett and Denzau estimated the equipment and support costs of a headend distributing forty simultaneous channels of prerecorded video programming (24). Interpolating their figures to determine the equipment required for a ten channel videotape distribution system,

Table 14: The Estimated Costs For A 1008 Terminal PLATO IV CAI System On the St. Louis Dedicated Educational Network

PLATO IV Equipment Costs	
Central Computing Facility	$6,000,000
One Network Interface Unit	30,000
1008 PLATO Terminals With Random-Access Audio System	5,544,000
59 PLATO Site Controllers	531,000
TOTAL CAPITAL INVESTMENT REQUIRED	$12,105,000
Total equipment cost per system operating hour*	$1263.15
Total communication cost per system operating hour**	1.41
Total support costs per system operating hour+	502.50
TOTAL COST OF PLATO IV SERVICE PER SYSTEM OPERATING HOUR FOR A 1008 TERMINAL SYSTEM	$1767.06

Communication cost per student contact hour equals 0.14¢

Total cost of service per student contact hour equals $1.75

---

*Equipment amortized over five years, with 2400 hours of operation per year. An interest rate of eight percent per year has been assumed.

**One forward channel and 300 kHz return bandwidth are required per network spoke.

+Assumes 2400 hours of operation per year. See text.

Table 15: The Estimated Costs for A 4032 Terminal PLATO IV CAI System On The St. Louis Dedicated Educational Network

PLATO IV Equipment Costs	
Central Computing Facility	$ 6,000,000
Four Network Interface Units	120,000
4032 PLATO Terminals With Random-Access Audio System	22,176,000
137 PLATO Site Controllers	1,233,000
TOTAL CAPITAL INVESTMENT REQUIRED	$29,529,000
Total equipment cost per system operating hour*	$3081.33
Total communication cost per system operating hour**	5.64
Total support costs per system operating hour+	510.00
TOTAL COST OF PLATO IV SERVICE PER SYSTEM OPERATING HOUR FOR A 4032 TERMINAL SYSTEM	$3596.97

Communication costs per student contact hour equals 0.14¢

Total cost of service per student contact hour equals $0.89

---

*Equipment amortized over five years, with 2400 hours of operation per year. An interest rate of eight percent per year has been assumed.

**Four forward channels and 1.2 MHz return bandwidth are required per network spoke.

+Assumes 2400 hours of operation per year, see text.

the required equipment and its 1971 cost are given below.

Ten Channel Videotape Distribution Equipment Costs

100 videotapes costing $13 each	$14,300
11 tape storage cabinets	3,300
One master recorder/duplicator	2,000
11 videotape recorders	11,000
TOTAL CAPITAL INVESTMENT REQUIRED	$30,600

An extra videotape recorder was included to allow for equipment down time. Amortized over a period of five years at an interest rate of eight percent, the cost of the equipment per system operating hour (assuming 2400 hours of operation per year) is $3.19.

The personnel required to operate the equipment and their yearly salaries are given below.

One clerk-librarian	$ 4,000
Five videotape recorder operators	25,000
One engineer-director (part-time)	8,000
TOTAL YEARLY PERSONNEL COSTS	$37,000

The cost of personnel per system operating hour is $15.42.

Finally, the communication cost of operating the videotape distribution system must be considered. Because we are assuming that viewers would be able to request that particular videotapes be shown, it might be realistic to say that instead of distributing each videotape to all of the network's users, which requires the use of ten forward channels per network spoke, requested videotapes would only be carried on the spoke serving the user who requested the videotape. If this limited distribution of videotapes is assumed, an average of two forward channels per spoke is required. In addition, one twenty kHz return audio channel over which system users could request videotapes is required per spoke. Because we are assuming that existing receiving classroom modules would be used to view the videotapes, the cost of forward and return bandwidth required for polling the receiving classroom modules has already been included in the cost of providing televised lectures; therefore, it will not be considered here. The hourly cost of two forward channels and 20 kHz return bandwidth per spoke is $2.68.

Thus, the total cost of providing videotape distribution services is $21.29 per system operating hour. Assuming that the system is used by eight viewers at each of the ten classroom modules able to simultaneously receive requested videotapes, the cost of viewing videotapes per user contact hour is 26.6 cents. It should be noted that although the ten channel videotape distribution system does not supply a large amount of services, the costs of a twenty, thirty, or forty channel system could easily be determined from the information given here. The maximum number of simultaneous videotapes able to be carried by the network is limited only by the amount of capital available for equipment and by the number of forward channels available on the dedicated network.

3.3.7 Facsimile Retrieval Of Documents From A Central Data Source

There presently are no completely automated systems available allowing users at remote locations to access documents stored in a central document collection. To indicate how inexpensively document transmission services might be provided on the dedicated educational network, however, the costs of a system allowing remote users to receive facsimile copies of documents stored on microfilm at a centralized location is considered here.

The Alden Model #9252 16mm Automatic Microfilm Scanner interfaced with Eastman Kodak's Miracode ® microfilm storage/retrieval system is an example of equipment that might be used to provide users of the dedicated network with remote access to documents stored at a central document collection. (The Alden microfilm scanner interfaced to the Kodak Miracode ® microfilm storage/retrieval system is sold by Alden as one unit. Miracode ® is a registered trademark of the Eastman Kodak Company.) With the equipment, the system operator is able automatically to search a manually selected 16mm microfilm cartridge to find a desired frame. Once the desired frame has been found, the unit scans the displayed information onto magnetic tape in twenty seconds. The information stored on the tape can then be automatically transmitted at one of four different selectable speeds, the choice of appropriate transmission speed depending upon the bandwidth of the communication channel used. Operating the unit at its fastest transmission speed, a typical 8 1/2 in. x 11 in. page can be transmitted over a 48 kHz bandwidth cable channel in forty-five seconds. (25) (At its fastest speed, the unit was intended for use with 24 kHz bandwidth broadband telephone lines. When used on a portion of the dedicated network's forward bandwidth, on the other hand, the unit's dual sideband modulated signal would require the use of 48 kHz of forward cable bandwidth.) The 1974 purchase price of the Model #9252 Alden/Micracode ® microfilm retrieval and facsimile transmission system is $46,000. (26) A facsimile receiver suitable for use at the institutions served by the network is the Alden Model #9257 recorder; its 1971 purchase price was $9500. (25)

Remote access to the central microfilm document base would be accomplished in the following manner. First, the user would inform the system operator which document was to be facsimiled. The retrieval unit's operator would then determine in which cartridge the document was stored and would load that cartridge into the microfilm retrieval/facsimile transmitter. After identifying the desired document through the retrieval unit's keyboard, the retrieval unit would search the cartridge for the desired document, and having found it, would scan the document, storing the information on magnetic tape. The stored information could then be transmitted to the user.

In estimating the costs of operating the document retrieval system, we assumed that one microfilm retrieval and facsimile transmission unit is at the system's headend, while one facsimile receiver is at each of the institutions served by the network. Interactive terminals are also required at each location to allow users at the system's remote facsimile receivers to request the transmission of documents from the central document collection. We assumed that the equivalent of Queset terminals allowing two way audio communication between users and the operators of the central document collection are installed at the headend and along with each of the facsimile receivers serving the network's forty-one users; the estimated cost per terminal is $230. (16) Thus, the capital investment required to provide document transmission services on the dedicated network totals approximately $445,000. Assuming that the equipment is to be amortized over a period of five years at an eight percent yearly interest rate and that the equipment would be operated a total of 2400 hours per year, the equipment cost per system operating hour is $46.44.

Forty-eight kHz of forward cable bandwidth is required per network spoke to accommodate facsimile transmissions; in addition, twenty-kHz bandwidth is required in each spoke's forward and reverse channels to allow two way audio communication between the facsimile users and the retrieval system's operator. Thus sixty-eight kHz of forward bandwidth and twenty kHz of return bandwidth are required per network spoke; referring to Table 10, the total hourly cost of the cable bandwidth required to provide facsimile services is two cents.

It is difficult to estimate exactly how many persons would be required to operate the facsimile document distribution system. Some of the larger institutions using the service might require a full-time operator at the facsimile receiver. Smaller institutions might only require that someone operate the facsimile receiver part of the time; furthermore, it is conceivable that some institutions would not have a facsimile operator at all, but instead would require users requesting documents to operate the equipment themselves.

To include all of these possibilities in our estimate of the personnel required to operate the remote document retrieval system, we assume that each of the forty-one institutions receiving the service requires an operator half-time. We also assume that two full-time operators would be required at the system's headend. Assuming that the forty-one institutional operators receive a half-time yearly salary of $2750, and that the total yearly salary of the two operators required at the headend is $11,000, then the yearly salary cost of the personnel required to operate the system is $123,750. This corresponds to a support cost per system operating hour of $51.56 assuming the system is to be operated 2400 hours per year. The total hourly cost of operating the facsimile service is $98.02; thus, each institution served by the network has access to the central document collection for a cost of $2.39 per hour. The hourly communication cost per institutional user is 0.05 cents.

3.4 A COMPARISON OF THE SERVICES ABLE TO BE OFFERED ON THE DEDICATED EDUCATIONAL NETWORK

The bandwidth requirements and capital costs of the services discussed in Section 3.3 are summarized in Table 16. Examining this table, three factors affecting the amounts of educational services able to be provided over a dedicated network are illustrated. The first and most obvious limitation to services provided is the initial capital investment required to purchase the equipment used in providing a sufficient amount of services. Two of the services listed in Table 16, videotape distribution service and community information service, have relatively small initial capital investment requirements only because they assume the availability of equipment used to provide other educational services. Of the other six listed services, it can be seen that four of the services require initial capital investments on the order of one-half to three-fourths the size of the capital investment involved in constructing the single cable return video dedicated network. The two remaining services, PLATO IV CAI systems capable of supporitng 1008 and 4032 terminals, require roughly twelve and twenty-nine times the initial capital investment required to build the single cable

Table 16: Capital and Communications Requirements Of The Services Able To Be Offered On The St. Louis Dedicated Educational Network

Service to be delivered	Cost of program origination equipment	Cost of receiving equipment	Capital Investment required	Equipment cost per system hour+	Forward channels required and per system hour cost++	Return channels required and per system hour cost++	Cost of support per system hour	Total cost per system hour
Televised lectures with return audio capability (15 simultaneous lectures, 1616 viewers)	$783,000	$195,000	$978,000	$102.05	15.02 per spoke cost $20.13 per system hour	425 kHz per spoke + 13 channels cost $3.62 per program hour	$255.00	$380.80
Central refresh TICCIT CAI (90 terminals)	$703,000	$72,000	$775,000	$80.87	225 kHz per spoke +83 channels cost $22.30 per system hour	225 kHz per spoke costs 6¢ per system hour	$64.38	$167.61
Remote refresh TICCIT CAI (90 terminals)	$319,000	$164,000	$483,000	$50.40	1.1 per spoke costs $1.47 per system hour	225 kHz per spoke costs 6¢ per system hour	$64.38	$116.31
Community Information Services*	—	—	—	—	1.1 per spoke costs $1.47 per system hour	225 kHz per spoke costs 6¢ per system hour	$64.38	$65.91
PLATO IV CAI (1008 terminal capacity)	$6,030,000	$6,075,000	$12,105,000	$1,263.15	1 per spoke costs $1.34 per system hour	300 kHz per spoke costs 7¢ per system hour	$502.50	$1,767.06
PLATO IV CAI (4032 terminal capacity)	$6,120,000	$23,409,000	$29,529,000	$3,081.33	4 per spoke costs $5.36 per system hour	1.2 MHz per spoke costs 28¢ per system hour	$510.00	$3,596.97
Videotape distribution (10 simultaneous programs, 80 viewers)**	$30,600	—	$30,600	$3.19	2 per spoke costs $2.68 per system hour	20 kHz per spoke costs 0.5¢ per system hour	$15.42	$21.29
Document retrieval by facsimile from central document file (one terminal at each of the 41 institutions served by the network)	$46,000	$399,000	$445,000	$46.44	68 kHz per spoke costs 1.5¢ per system hour	20 kHz per spoke costs 0.5¢ per system hour	$51.56	$98.02

---

*Assumes existing remote refresh TICCIT equipment will be used after hours to provide community information services to the public; therefore, no additional equipment is required. Usage assumption is 4 hours per day, 300 days per year.

**Assumes existing receiving classroom modules used with televised lecture service would also be available to receive videotapes; as a result, no additional receiving equipment is required.

+Equipment amortized over a period of five years; unless otherwise stated, 2400 hours of system operation per year is assumed. An interest rate of eight percent per year has been assumed.

++Cable network amortized over a twenty year period with an eight percent yearly interest rate and 2400 hours of operation per year assumed. The hourly cost figures for the use of cable bandwidth assume that all available cable channels (35 forward plus 4 return channels per spoke) are being used.

return video dedicated network.

The second factor limiting the amount of an educational service that can be provided over the network is the cable bandwidth required by each service when compared to the amount of bandwidth available on the network. In spite of the fact that the educational institutions associated with the dedicated network could provide enough televised instruction to require the use of eighteen studio classrooms, limitations in the amount of return bandwidth available on the network restrict the number of televised lectures able to be simultaneously presented to fifteen. Similarly, although a single centrally refreshed TICCIT system can support only ninety terminals, no more than one centrally refreshed TICCIT system can be used on the single cable networks without utilizing all of the forward channels available to TICCIT in our design.

The third factor limiting the level of services that can be provided is the number of users that must be served by any portion of the network. This was best illustrated in the assumed allocations of centrally refreshed TICCIT terminals. Had the system's ninety terminals been equally distributed among the forty-one institutions served by the network, each instution would have the use of at least two centrally refreshed TICCIT terminals. But because fully half of the forty institutions (excluding Washington University) remotely located from the headend are served by the network's first spoke (Figure 1), equal allocation of centrally refreshed TICCIT terminals requires that forty forward channels be available in spoke one to distribute TICCIT services.

A fourth factor affecting the level of services that can be provided is illustrated by Table 17, which lists the cost of the various services considered on a per user contact hour basis. All of these costs were determined by dividing the hourly cost of operating each service by the number of persons able simultaneously to use the service. The per contact hour costs of receiving PLATO IV CAI services were estimated for two cases. In the first case, it was assumed that the system's central computing facility could support only 1008 terminals. Under this assumption, the system's required capital investment was $12,105,000 while the cost of PLATO service per student contact hour was $1.75. If, on the other hand, it is assumed that the central computing facility of the PLATO system could support up to 4032 terminals, the capital investment required increases to $29,529,000 while the cost of PLATO services per student contact hour decreases to $0.89. The reduction in the cost of PLATO services is due to the cost of the central computing facility and the cost of many of the PLATO site controllers being spread among more users in the system serving 4032 terminals. This serves to illustrate that even though the initial investment required to offer a service might be comparatively small, if relatively few people use it, the actual cost of providing the service might be higher than would be expected.

One further comment concerning Table 17 should be made. In an effort to determine if a dedicated coaxial cable system could be used to deliver educational services at a lower cost than could other types of communication systems, we computed the per user contact hour cost of distributing each of the services on the

Table 17: Costs On A Per User Contact Hour Basis Of Services Able To Be Offered On The St. Louis Dedicated Educational Network

Service to be delivered	Communication cost per user contact hour	Total cost per user contact hour
Televised lectures with return audio capability (15 simultaneous lectures, 1616 viewers)	1.5¢	$0.24
Central refresh TICCIT CAI (90 terminals)	25.0¢	$1.86
Remote refresh TICCIT CAI (90 terminals)	1.7¢	$1.29
Community Information Services	1.7¢	$0.73
PLATO IV CAI (1008 terminal capacity)	0.1¢	$1.75
PLATO IV CAI (4032 terminal capacity)	0.1¢	$0.89
Noninteractive video tape distribution (10 simultaneous programs, 80 viewers)	3.3¢	$0.27
Document retrieval by facsimile from central document file. (one terminal at each of the 41 institutions served by the network)*	0.05¢	$2.39

---

*Costs given per user contact hour for document retrieval by facsimile from central document file refer to the cost per institution per hour for the service.

dedicated cable network. Referring to Table 17, it can be seen that except in the case of central refresh TICCIT services, the cost of the cable bandwidth required to distribute each of the services is less than one-tenth of the total cost of providing the educational services. Thus, it is felt that a dedicated coaxial cable network does represent an efficient method of distributing interactive and noninteractive educational services in the St. Louis metropolitan area.

Furthermore, the existence of a broadband transmission system like the dedicated network would allow institutions having little or no "in-house" computing resources to timeshare the excess computing capacity of any other institution served by the network at minimal cost. Normally, remote timesharing is accomplished using specially conditioned leased telephone lines for which the institution pays a premium price. For example, the cost of a leased voice grade telephone line having C2 conditioning (which is typically required for signals having data rates greater than 4800 bits per second and being sent a distance of fifteen miles or greater) includes a $27.00 per month charge for line conditioning in addition to monthly charges of $8.80 per mile for the use of the leased telephone line. (27) If it is assumed that timesharing services would be in use eight hours per day on twenty-five days per month, a bidirectional 680 kHz channel could be established between any two institutions served by the network for less than the $27.00 monthly charge for the C2 conditioning of a voice grade telephone line, a considerable savings.

4. SUMMARY AND CONCLUSIONS

4.1 PURPOSE OF THE REPORT; RELATION TO OTHER WORK

This report, used in conjunction with its companion document, (1) is intended to serve as a useful systems design tool in an engineering and economic study of communications technology applied to education. However, it also includes much descriptive material useful to the nontechnologist interested in educational networking. For the engineering study, the report provides an important part of both the background information and the analysis necessary to conceptualize and evaluate alternative communications networking schemes for the delivery of educational services.

In the companion document to this report, the background information provided gives the designer of educational networks a broad engineering overview of the range of educational services deliverable by communications technology. We review the capabilities, costs, and communications requirements of these services. As additional background, a brief description is given of existing educational networks such as those currently serving broadcast educational radio and television.

To undertake an analysis of each type of communications network that might be used to deliver educational services would have been a task beyond the scope of this report. The required information, however, is available in numerous texts, journal articles, and engineering design handbooks. Therefore, what has been undertaken here is a discussion of some of the factors affecting the design of one particular class of communications networks, dedicated coaxial cable networks, in an effort to illustrate to the reader the range of considerations that must be included in a design of a realistic educational network. Examined were the technical characteristics of coaxial cable networks, and these were discussed for the purpose of illustrating the types of limitations that are encountered in the design of a communications network. It is felt that the information presented here, when used in conjunction with other available results, should provide a relatively complete basis from which an educational network designer can work.

In addition, a number of other issues, not specifically technical, will determine the success of the network configurations formulated to serve the requirements on any given area. Two examples are, first, the identity and the needs of users of the network, and second, how any by whom the network could be controlled and supported. The identity of the users of the networks designed in this work to serve the St. Louis metropolitan area was considered only to the extent that a group of institutions that might be able to support the services offered over the network was identified. No analysis of their needs was undertaken; rather, we listed the services able to be delivered over the network, along with the services' required capital investments, communications requirements, and a determination of the cost of each service calculated on a per user contact hour basis. Similarly, the administrative framework under which the network would operate was not considered. Related topics, however, have been the subject of intensive research at the Center for Development Technology and elsewhere. The result of much of the Center's work in these areas are available in companion documents. (6) (28-34)

4.2 SUMMARY OF FINDINGS

The rest of this summary section briefly reviews the work of this report and its companion document. (1) This review is intended to highlight the conclusions developed in the course of our work.

The companion document to this report begins by describing the broadcast media: FM radio, AM radio, and VHF and UHF television. Although the broadcast media are mostly limited to noninteractive programming, they allow educational programming to be delivered inexpensively through existing receivers to large numbers of learners spread over areas now impractical to serve by other means. The costs and coverage abilities possible for each type of educational broadcast medium are considered, along with the channel capacity of each medium and the number of channels available. Comparing FM and AM broadcast radio, we find that for most noninteractive audio educational programming FM radio is superior to AM radio for most educational uses, because cost are similar to AM, it has available dedicated educational channels, higher fidelity, and the ability to distribute several channels of programming per radio channel. However, in cases where large, sparsely populated areas are to be served, AM broadcasting might provide the only practical broadcast distribution method for educational radio. Similarly, because of VHF television's higher possible coverage and the existence of superior VHF tuners in most existing privately owned television receivers, VHF television is technically preferable to UHF television even though most of the channels available for use today are located in the UHF television band.

As examples of options possible when designing a CAI system or implementing other interactive educational services, we examine two experimental interactive networks with educational applications: the MITRE Corporation's TICCIT systems and PLATO IV developed by the University of Illinois at Champaign-Urbana. The TICCIT systems use a minicomputer to provide CAI services, including computer selected audio and color television displays, either full-time to 128 dedicated institutional terminals or part-time to up to 1000 home terminals. The actual number would depend largely on the cable capacity and the amount of services to be delivered daily to each terminal. We find that if TICCIT services are delivered to remote terminals over a cable system on a part-time basis using a central refresh topology, the probability of the user having to wait before services become available is very dependent on the number of system users and the amount of services each user requests. However, if the terminals receive enough use to justify the cost of placing a video refresh memory at each of the users' premises, the amount of TICCIT services able to be delivered depends only upon the capacity of the minicomputer used, and additional computer systems can be added to provide increased levels of service.

The PLATO system uses a large general-purpose computer and innovative display technology to allow versatile CAI either to be distributed long distances over low bandwidth lines or to allow up to 1008 PLATO terminals to be served through a single 6 MHz bandwidth cable channel. Examining system hardware costs and the amounts of service the PLATO system provides, we find that the present developmental PLATO system can serve only 1008 terminals (rather than 4032 terminals the system is designed to serve) because of the heavier-than-expected load that users are presently placing on the system. The assumptions concerning the amount of system use that can be expected and the cost of producing sufficient courseware to attract enough system users to ensure that the cost of PLATO CAI remains reasonable are also analyzed. As a general conclusion, we find that the design assumptions made in these areas by PLATO's developers were optimistic.

We examine the Bell System's proposed Picturephone ® service, a third interactive communications network and the only one with two-way point-to-point video capability, for its applicability in carrying educational services. Because of its low resolution and high communications cost, Picturephone ®, if implemented in its planned form, is unsuitable for use in any foreseeable educational communications application.

Several technologies which might be used to supply interactive library and document transmission services over future educational communications networks are examined. Facsimile and slow-scan television, which are currently in use for document transmission, are likely to be too expensive and inconvenient to be widely used to provide services to individuals in future educational applications. However, facsimile might be used to supply document transmission to regional terminals, at which point users could pick up requested materials.

The resolution requirements of the displays needed to provide interactive library services at user terminals are discussed, as well as the various display/refresh memory combinations which might be successfully used to meet the requirements. The selection mechanism needed in a remote microfilm based library system and a promising and relatively new devleopment, interactive indexing systems, are also described.

In this report, we discuss the technical and economic factors affecting the design of one class of educational networks, dedicated coaxial cable networks. To show how the information is used in a system design, we develop the designs of single and dual cable dedicated networks that might be used to deliver educational services to selected institutions in the St. Louis metropolitan area. The networks described have the capacity to simultaneously distribute thirty-five forward and four return, or seventy forward and eight return, six MHz bandwidth channels of programming respectively. In estimating the cost of building each of the networks, we find that a dedicated cable network can be built at the same time that other cable construction is being done, or if a second dedicated cable allowing for future expansion is installed when the first dedicated cable is being installed, a great savings in network construction cost will be realized.

Combining the services discussed in the companion report with the single cable return video network presented in Section 2 of this report, we estimate the required capital investment, cable bandwidth, and the amount of each service that can be offered over the network serving institutions in the St. Louis metropolitan area. In addition, we determine both the communications cost and the total cost of providing each of the services.

This information can be used by the planners or designers of educational networks in two ways. First, it provides a first estimate of the cost of offering each service to institutional users of dedicated networks in similar metropolitan areas. In addition, using the information presented together with the information available in numerous engineering design handbooks, the network designer can estimate the cost of supplying each of the services using a different communications system more appropriate to his own particular requirements.

Having investigated the factors affecting the cost of providing each service over the coaxial cable dedicated network, we can make several statements concerning the use of dedicated networks to deliver educational services to institutional users. First, referring to Table 16, it can be seen that the capital investment required for the equipment used to provide each service is on the order of the total cost of building the coaxial cable networks. Thus, the communications system itself should entail only a small part of the total cost of the educational network. This fact is further pointed out in the communication cost per student contact hour determined for each service in Table 17. Assuming that enough demand for the network services exists so that the dedicated cable network will be used to capacity, the cost of the cable bandwidth required to deliver each of the services is in all but one case less than four cents per user contact hour. This illustrates that a dedicated cable network is an inexpensive means of delivering interactive educational services to institutional users in metropolitan areas.

Finally, by comparing Tables 16 and 17, it can be seen that although a large capital investment would be required to build a dedicated cable network carrying much versatile educational programming, the cable's large bandwidth and its reasonably large possible area of coverage allow enough users to share the services that the cost per service, when expressed on a per user contact hour basis, is relatively small.

For the technical design of a network fulfilling a particular area's needs, the reports provide a relatively complete information base from which to work. It should be noted, however, that before the design of a network can realistically be undertaken, an identification of network users must be made and the users' needs must be analyzed. The network designs for the St. Louis area presented here were intended primarily to allow illustration of the technical principles of coaxial cable network design and to allow estimates of the cost of providing each educational service to be made. Therefore, no survey of the area's needs was undertaken. The first step in the design of an operational dedicated educational network for the St. Louis area would be to conduct such a survey. We do, however, offer first estimates of the cost of providing educational services to institutional users in the St. Louis area, and, using the information presented here, the technical design of more representative dedicated networks for the St. Louis area could be undertaken.

APPENDIX 5.1

TECHNICAL CONSIDERATIONS IN THE DESIGN OF COAXIAL CABLE COMMUNICATION NETWORKS

5.1.1 Introduction

The performance of a coaxial cable transmission system carrying video signals can be specified by three characteristics of the signals to be received at the point in the network farthest from the headend. These characteristics are the minimum acceptable signal-to-noise ratio (SNR), the maximum allowable signal distortion caused by amplifier nonlinearities, and the power level at which signals are to be transmitted through the system. A fourth system performance measure, the tolerance of the system, is the range over which signal's power levels can vary without causing excessive signal degradation.

In this Appendix, we will derive the equations allowing the system designer to determine whether a given coaxial cable transmission system will allow signals to be distributed without excessive degradation. The effects of using different types of coaxial cable and repeater amplifiers are examined, and a method allowing the designer to predict the maximum distance over which the cable system will acceptably operate is presented. Finally, we discuss the different technical requirements of a system allowing bidirectional digital signal transmission and unidirectional video signal transmission as compared to a network allowing bidirectional transmission of digital and video signals.

5.1.2 Cable System Design Considerations

5.1.2.1 Signal Degradation Due To Noise

The amount of noise generated in a coaxial cable transmission system can be attributed to two sources. The first source is random noise caused by thermal agitation of the electrons in the conductors associated with the programming source itself. For a thermal noise source, the available r.m.s. noise power in a one Hz bandwidth is given by (1)

$$p_n(f) = kT \text{ watts/Hz} \qquad [5.1.1]$$

where k = Boltzmann's constant = 1.3805×10^{-23} joules/$^{\circ}$K. and T is the temperature of the noise source expressed in $^{\circ}$K. The amount of r.m.s. noise power that can be coupled into an external load from a 4 MHz bandwidth source (which corresponds to the normalized bandwidth of a television video bandpass filter (2)) at room temperature (20° C.) is 1.62×10^{-14} watts.

In cascaded amplifier systems, it is more convenient to express power levels in terms of decibels above a given reference level. Defining 0 dBmV as the power level of a one millivolt signal across 75 ohms (which is equivalent to a signal power level of 1.33×10^{-8} watts), the noise generated in the program source has a level of -59.2 dBmV. This is the smallest amount of noise interference that will have to be overcome anywhere in the system.

The second source of noise in coaxial transmission systems is the repeater amplifiers that are situated periodically along the cable; their gain compensates for the attenuation signals receive in the coaxial cable. These amplifiers, in addition to amplifying the signals and the noise that are applied to their inputs, generate some internal noise which combines with the signal being amplified. Thus, the amount of noise power present at the amplifier's output is greater than the noise power at the input of the amplifier multiplied by the amplifier's gain. The difference in noise power levels measured linearly is called the amplifier noise factor (n.f.); the difference in noise power levels measured in db. is called the amplifier noise figure (N.F.). The relationship between noise factor and noise figure is given by

$$\text{N.F.} = 10 \log_{10} \text{n.f.} \qquad [5.1.2]$$

As the length of a coaxial transmission system increases, the number of amplifiers that must be cascaded to compensate for cable attenuation increases; similarly, as the number of amplifiers cascaded increases, the total amount of noise generated in the system also increases. The total amount of noise power that is generated by a cascaded amplifier system can be computed as follows. Consider a cascade consisting of two repeater amplifiers interconnected by a length of coaxial cable. Assume that the amplifiers have (linear) gains of g_1 and g_3 and have noise factors of f_1 and f_3, respectively. Assume the cable has a gain of g_2 (approximately equal to the reciprocal of g_1). The noise factor of a cable having a gain G is equal to G^{-1}; (3) thus, the cable in the cascade has a noise factor f_2 equal to $1/g_2$. The noise factor of the three devices connected in succession is given by (3)

$$f_{123} = f_1 + \frac{f_2 - 1}{g_1} + \frac{f_3 - 1}{g_1 g_2} = f_1 + \frac{f_3}{g_1 g_2} - \frac{1}{g_1} . \qquad [5.1.3]$$

This formula can be iterated to determine the noise factor of a 2N+1 element cascade consisting of N+1 amplifiers having gains of $g_1, g_3, \cdots, g_{2N+1}$ and noise factors $\frac{1}{g_2}, \frac{1}{g_4}, \cdots, \frac{1}{g_{2N}}$ respectively. Iterating equation 3, the noise factor of a 2N+1 element cascade is given by

$$f_{1:2N+1} = f_1 + \sum_{i=1}^{N} \left[\frac{f_{2i+1}}{\prod_{j=1}^{2i} g_j} \right] - \sum_{i=1}^{N} \left[\prod_{j=1}^{2i-1} g_j \right]^{-1} . \qquad [5.1.4]$$

Terms of the form $\prod_{j=1}^{2i} g_j$ represent the gain of the cascade measured at the input of the (i+1)th amplifier, while terms of the form $\prod_{j=1}^{2i-1} g_j$ represent the gain of the cascade measured at the output of the (i)th amplifier. The noise figure for the entire cascade is given by

$$F_{tot} = 10 \log_{10}(f_{1:2N+1}). \qquad [5.1.5]$$

In some cases, only an approximation of the cascade noise figure will be needed. Assuming that all of the amplifiers used have G db. gain and an F db. noise figure, while the lengths of cable connecting the amplifiers attenuate signals by G db., the noise figure of an N-amplifier cascade is approximated by

$$F_{tot} = F + 10 \log_{10} N. \qquad [5.1.6]$$

Having determined the value of F_{tot} for the particular cascade being analyzed, the single channel noise power level at the cascade's output is given by

$$\text{Noise Power}_{out} = -59.2 + G_{tot} + F_{tot} \text{ dBmV}, \qquad [5.1.7]$$

where G_{tot} is the cascade gain expressed in decibels (that is, the difference in signal levels at the cascade's input and output).

The noise generated in the cable transmission system affects system design in the following way. If video signals are to be received with acceptable quality, the signals must be propagated at a power level high enough to insure that a minimum signal-to-noise ratio is maintained; too low a power level will cause received transmissions to be excessively degraded with "snowy" interference. In the networks designed in this Appendix, the minimum signal-to-noise ratio that will be allowed to exist at the far ends of the system is 43 db. (referenced to a 4 MHz noise bandwidth). This would correspond to most users of the system experiencing TASO Grade 5 (excellent) reception. (3,4) To ensure that the minimum signal-to-noise ratio experienced anywhere in the system is 43 db., the minimum allowable power level at which signals can be propagated (measured at the outputs of the forward amplifiers) is given by

$$S(\text{min}) = -59.2 + G_{tot} + F_{tot} + 43 \text{ dBmV}, \qquad [5.1.8]$$

where F_{tot} and G_{tot} are defined in equations 5.1.5 and 5.1.7.

5.1.2.2 Signal Degradation Due To Distortion

Two types of nonlinear distortion occur in cascaded amplifier systems. The distortion occurs because the transfer characteristics of the amplifiers used are not strictly linear, but instead are closely approximated by

$$V_{out} = a_1 \times V_{in} + a_2 \times (V_{in})^2 + a_3 \times (V_{in})^3. \qquad [5.1.9]$$

The first kind of distortion, intermodulation distortion, results in the generation of spurious signals having frequencies at the sum or difference of the frequencies present in the amplifier's input signal; these spurious signals interfere with the reception of desired signals in the same frequency band. Second-order intermodulation distortion products have frequencies of the form 2A or $A \pm B$, where A and B are frequencies of signals present at the amplifier's input. Spurious products having frequencies 3A, $2A \pm B$, $A \pm 2B$, and $A \pm B \pm C$ are referred to as third-order intermodulation distortion products. When excessive intermodulation distortion is generated, the distortion products combine ("beat") with the carriers of channels in use to create "herringbone" interference patterns in the received video signals. (3)

The second type of distortion generated in cascaded amplifier systems, cross-modulation distortion, occurs when the modulation of one signal carried by the transmission system is weakly transferred to the signal carried on another cable channel. This occurs because the gain of the amplifiers used is not time-invariant, but varies as a function of the magnitude of their input signals. Since the signals carried on the cable network are modulated with a form of amplitude modulation (vestigal sideband modulation), each signal, with its instantaneous magnitude changing at a video rate, will cause the instantaneous gain of each amplifier also to change at a video rate. This changing amplifier gain amplitude modulates each of the signals carried on the cable system, allowing the modulation of one signal to be superimposed upon other signals' modulation.

Cross-modulation distortion results in a weak reproduction of the video information of the interfering channel being superimposed upon the information carried in the other network channels. Because the component of a standard NTSC television signal having the greatest amplitude is the signal's horizontal sync pulses, the effect of excessive cross-modulation distortion on received signals is to cause slanting bars to be perceived in the received picture. If the interfering signal has the same horizontal frequency as the signal being viewed, the interfering bars will be stationary. More commonly, the signals carried on the cable system will have slightly differing horizontal frequencies; as a result, the interfering bars will shift back and forth across the received picture, giving it a "windshield wiper" effect. (3)

Cross-modulation is usually measured as one hundred times the ratio of the cross-modulation caused variation in the peak voltage of an otherwise unmodulated signal to the unmodulated signal's peak voltage; the result is a number between zero and one hundred percent. For reasons similar to those used in noise calculations, it is often more convenient to express the percentage cross-modulation in decibels with respect to one hundred percent cross-modulation. Because percent modulation implies a voltage measurement, this conversion is given by

$$XM(\text{db. rel. to } 100\%) = 20 \log_{10} \frac{\%\ \text{cross-mod.}}{100\%} \qquad [5.1.10]$$

In the remainder of this Appendix, percentage cross-modulation in decibels with respect to one hundred percent cross-modulation will be signified XM(db.).

The type of nonlinear signal distortion ultimately limiting the performance of a cascaded amplifier transmission system is dependent upon the number of channels carried on the system and upon the frequency assignments used for the channels. In a cable system carrying less than twelve channels, the effects of intermodulation distortion generated in the system have usually been insignificant when compared to the effects of cross-modulation distortion generated at signal levels normally used in cable trunk systems. Switzer (5) states, however, that practical experience with cable televisions systems which have increased their channel capacity beyond twelve channels by the use of broadband amplifiers has shown that third-order intermodulation distortion becomes the dominant type of distortion limiting cable system performance. Two comments, however, one the effects of cross-modulation and intermodulation distortion can be made.

First, unlike the effects of cross-modulation distortion, third-order intermodulation effects can be reduced by phaselocking all carrier and pilot signal frequencies carried on the cable to harmonics of a single reference oscillator. (5) By doing this, all third-order distortion products of the form A-B+C or A+B-C are caused to fall zero-beat on existing carriers. The resulting reduction in "beat" interference causes the effects of a given level of third-order intermodulation distortion to be much less visible, and would probably cause cross-modulation distortion to again become the dominant type of distortion limiting cable system performance.

Second, it should be noted that cross-modulation distortion, like third-order intermodulation distortion, is primarily a result of the cubic term in the transfer characteristics of the cable amplifiers used (see equation 5.1.9); the two types of distortion are considered separately only because they each affect the received images differently. Because of this fact, the same procedure used to reduce cross-modulation distortion will similarly reduce third-order intermodulation distortion.

In the network designs given here, we assume that cross-modulation distortion will be the dominant form of distortion. The amount of cross-modulation distortion a system will generate depends upon three factors. First, in a cascaded amplifier system of N amplifiers, the total percentage cross-modulation generated in the cascade is given by

$$(\%XM)_{tot} = \sum_{i=1}^{N} (XM)_i \qquad [5.1.11]$$

where $(\%XM)_i$ is the percentage cross-modulation generated within the (i)th amplifier in the cascade. Thus, if each amplifier in the cascade generates an equal amount of distortion, the total percentage distortion generated is given by

$$(\%XM)_{tot} = N \times (\%XM)_1 . \qquad [5.1.12]$$

Expressed in decibels relative to one hundred percent cross-modulation, the total amount of cross-modulation distortion generated by the N-amplifier cascade is given by

$$XM(db.)_{tot} = XM(db.)_1 + 20 \log_{10} N, \qquad [5.1.13]$$

where $XM(db.)_1$ is the percentage cross-modulation in decibels of any of the cable amplifiers in the cascade.

The second factor affecting the amount of cross-modulation distortion generated in a cascaded amplifier system is the level at which signals are propagated through the system. Referring to equation 5.1.9, consider what happens when v_{in}, the signal voltage applied at the input of a repeater amplifier, is doubled. The voltage of the desired linear term of the amplifier's output signal, $a_1 \times v_{in}$, is increased by a factor of two. The voltage of the cubic term of the amplifier's output signal, on the other hand, is increased by a factor of eight. Thus, the signal to third-order distortion voltage ratio is decreased to one-fourth its previous value.

An increase of one db. in the level at which signals are carried in a cascaded amplifier system causes an increase of two db. in the relative amount of cross-modulation distortion generated in the system. Similarly, a decrease of one db. in the level at which signals are carried in a cascaded amplifier system causes a decrease of two db. in the relative amount of cross-modulation distortion generated in the system. More generally, given two signal levels, S_1 and S_2, the effect signal levels have on the amount of cross-modulation distortion generated is described by

$$XM(db.)_{S_2} = XM(db.)_{S_1} + 2(S_2 - S_1) \text{ db.}, \qquad [5.1.14]$$

where $XM(db.)_{S_2}$ and $XM(db.)_{S_1}$ are the amounts of cross-modulation distortion measured in decibels relative to one hundred percent distortion that are generated at signal levels of S_2 and S_1 dBmV, respectively. A general observation that can be made is that for a given system, there is a maximum level at which signals can be propagated if excessive distortion is to be avoided.

The third factor affecting the amount of cross-modulation distortion generated is the number of channels being carried within the system. The number of channels carried affects the amount of distortion generated because each additional channel on the system makes it possible for additional distortion products to be generated. Depending on the timing characteristics of the programming carried on the system, the effect changing the number of channels carried has on cross-modulation distortion generated is estimated in one of two ways.

Recall that the effect of cross-modulation distortion upon received television images was to produce slanting bars in the received images; the bars themselves are images of the sync pulses carried on the interfering channels. Worst case interference occurs when the interfering signals have synchronous timing (i.e., when each signal's timing is derived from a common source). In that case, the slanting bars produced by each interfering channel in the received image are superimposed, and their interference is much more discernible. Given a cascaded amplifier system generating $XM(db.)_K$ cross-modulation distortion when operating at a given signal level and carrying K channels of synchronous programming, if the number of channels of synchronous programming carried is changed to M channels, the resulting cross-modulation distortion generated is given by (3)

$$XM(db.)_M = XM(db.)_K + 20 \log_{10} \frac{M}{K}. \qquad [5.1.15]$$

This equation assumes an equal amount of cross-modulation is generated by each interfering channel. While this would provide an adequate estimate of cross-modulation generated in most cases, to obtain a more accurate measurement of the cross-modulation distortion the operator could measure and total each channel's contribution to the system's cross-modulation distortion.

Synchronous cross-modulation interference occurs only if all of the programming carried on a system originates from a single location; more, commonly, the programming carried on a system originates from several locations. As a result, the programs' horizontal frequencies vary slightly from one channel to the next, and the cross-modulation distortion generated by each channel adds randomly rather than synchronously. The result of randon addition is that many weak, slanting bars rather than one well defined slanting bar are seen by viewers. Viewers seem to find that the effect of the random interference is less noticeable; this subjective evaluation is reflected in the CATV design rule of thumb that states that the interference in the case of randomly modulated signals increases only one-half db. for every one db. increase that would occur if the signals were synchronously modulated. (3) Specifically, given a cascaded amplifier system generating $XM(db.)_K$ cross-modulation when operated at a given signal level and carrying K channels of randomly modulated programming, if the number of randomly modulated channels of programming carried is changed to M, the resulting cross-modulation distortion generated is given by

$$XM(db.)_M = XM(db.)_K + 10 \log_{10} \frac{M}{K}. \qquad [5.1.16]$$

In equations 5.1.13 through 5.1.16, we described how the number of amplifiers in a cascade, the level at which signals are carried in a cascade, and the number of channels carried by a cascade affects the amount of cross-modulation distortion generated in a cascaded amplifier system. These equations can be combined into one equation describing the effect all of these factors have upon the amount of cross-modulation distortion generated. Assume that a cable system is to use cable amplifiers each generating $XM(db.)_1$ cross-modulation distortion when carrying K channels of programming at a signal level of S_1 dBmV. If a cascaded amplifier system of N amplifiers carrying M channels of programming at a signal level of S_2 dBmV is to be constructed, the amount of cross-modulation distortion that will be generated by the cascade is given by

$$XM(db.)_{tot} = XM(db.)_1 + 20 \log_{10} N + 2(S_2 - S_1) + 10 \log_{10} \frac{M}{K}. \qquad [5.1.17]$$

This equation assumes that the channels carried have nonsynchronous modulation.

The maximum level of cross-modulation distortion that can be tolerated has not been agreed on. Simons reports that a cross-modulation limit of -46 db. at the television receiver's r.f. input should produce just perceptible interference. (3) Past CATV industry practice, however, has been to design trunk systems and distribution systems so that each contributed -57 db. cross-modulation distortion, for a system total cross-modulation distortion figure of -51 db. The cable systems designed here, therefore, will be allowed to have a maximum level of cross-modulation distortion of -51 db.

5.1.2.3 The Effects Of Received Signal Level Upon Signal Quality

The third signal characteristic specifying the performance of a coaxial cable system is the level at which signals are delivered to users' premises. In the noise calculations done previously, we considered the amount of noise generated in the cable system, but not the amount of noise generated in individual television receivers. Television receivers' noise figures range from 4.6 db. to 12.2 db., depending upon the design quality of the receiver and upon the particular channel being viewed. (6) At received signal levels much below 0 dBmV, the additional amount of noise generated in a receiver having a high noise figure can cause the received images to have excessive "snowy" interference. For received signal levels above 0 dBmV, however, the amount of noise generated in individual receivers has an insignificant effect on the quality of the received images. Thus, the minimum signal level that should be delivered to users' premises is 0 dBmV.

Similarly, there is a maximum signal level above which signals should not be delivered to users' premises; the maximum level depends upon the overload and reradiation characteristics of the receiving equipment used. Present CATV design practice is to set this level at no more than 10 dBmV. (6) It should be noted, however, that the signal level at the users' premises can always be reduced by the use of attenuators. Thus, the maximum delivered signal level is not actually a constraint in the design of coaxial cable networks.

5.1.2.4 Limits To Cable System Length and Channel Capacity

We can now consider the way in which these signal characteristics, signal-to-noise ratio, the amount of cross-modulation distortion generated, and the level at which the signals are delivered to users, limit the length and the channel capacity of a coaxial cable network. Equation 5.1.8 specifies the minimum signal level that must be maintained excessive signal degradation due to noise is to be avoided.

$$S(\text{min}) = -59.2 + G_{tot} + F_{tot} + 43 \text{ dBmV}. \qquad [5.1.8]$$

This value of S(min) will ensure that a minimum of 43 db. SNR is maintained. Equation 5.1.7 relates the total amount of cross-modulation distortion generated within a cascade to the number of channels being carried, the number of amplifiers within the cascade, and the output signal levels at which the amplifiers are operated. Using the forward amplifiers whose specifications are listed in Table 5.2.3 of Appendix 5.2 and assuming that thirty-five forward channels will be carried on the network, it can be shown that assuming a maximum of -51 db. cross-modulation distortion will be tolerated, the maximum signal level that can be carried on the network's forward channels is given by

$$S(\max) = \frac{-51 - (-89)}{2} - 10 \log_{10} N + 35 \text{ dBmV} \qquad [5.1.18]$$

where N is the number of amplifiers in a cascade. Thus, the maximum level at which signals can be propagated on the network is given by

$$S(\max) = 54 - 10 \log_{10} N \text{ dBmV}. \qquad [5.1.19]$$

Equations 5.1.8 and 5.1.19 respectively give the lower and upper bound for the range of signal levels over which a cascaded amplifier system may be operated without causing excessive signal degradation due to noise and distortion. Examination of the two equations reveals several things. First, S(max) and S(min) will converge as N, the number of amplifiers in the cascade, increases. (S(min) increases as F_{tot}, the total noise generated in the cascade, increases.) Since, by definition, the value of S(min) must be less than or equal to the value of S(max), it follows that there is a limit upon the number of amplifiers that can be cascaded without causing excessive signal degradation. The maximum number of amplifiers that can be cascaded is approximated by

$$N(\max) = \text{antilog}_{10} \left[\frac{S(\max) - S(\min)}{20}\right] \qquad [5.1.20]$$

where S(max) and S(min) have been calculated for N = 1 (i.e., for a single amplifier). Furthermore, because the values of S(min) and S(max) converge at an equal rate as N approaches N(max), it follows that the output level at which signals should be maintained is given by

$$S(opt) = \frac{S(max) - S(min)}{2} \quad \text{for } N \geq 1. \qquad [5.1.21]$$

The absolute maximum number of amplifiers that may be cascaded in an ideal coaxial cable transmission system is given by equation 5.1.20; the number of amplifiers able to be cascaded in a practical system, on the other hand, is much less than N(max). This is a result of the assumptions made in determining N(max). In particular, we assumed that the average gain of each amplifier was constant; we also assumed that the attenuation characteristics of the lengths of cable between amplifiers were constant. (Both these assumptions are embodied in the assumption that each amplifier in the cascade will operate at the same signal level, and therefore will each contribute the same amount of noise and distortion.) Neither of these assumptions, however, is necessarily true. Although the cable amplifiers when installed might have equal gains, as amplifier components age, the average gain exhibited by each amplifier can vary. In addition, the attenuation of a length of cable is temperature dependent; cable loss increases one percent for each ten degree Fahrenheit increase in cable temperature. (7)

The effect of these variations on system design is that a cable system must be designed with a sufficient range between S(min) and S(max) to allow for the signal level variations that will occur due to amplifier aging and temperature changes. The difference between S(min) and S(max) is termed the system's tolerance. Because it specifies the range of signal levels which may be acceptably carried over the system, it can be considered a measure of the system quality.

There are two criteria by which the tolerance needed in a cable system is determined. The maximum tolerance needed corresponds to the range of signal levels over which the automatic gain control circuitry in the amplifiers used can compensate. Two types of amplifiers are used in cable networks. The first, manual gain amplifiers, have a fixed gain which is preset at the time of installation. The second type of amplifier used incorporates automatic gain control circuitry that typically will constrain forward signal output levels to within ±0.5 db. for a ±4.0 db. change in the input signal level. Use of these amplifiers periodically in the cascade ensures that excessive signal level variation, with accompanying distortion or noise buildup, will not occur due to environmental factors. But because these amplifiers will only operate suitably over a limited range of input signal levels, the cable system is designed so that excessive shifts in signal levels cannot occur between automatic gain control (AGC) amplifiers. Thus, the maximum tolerance needed is equal to the range of signal levels over which the amplifiers' AGC circuits can operate (typically eight db.).

On the other hand, designing a system for maximum needed tolerance limits the number of amplifiers that may be cascaded, and in some cases, would make it impossible for all of the distant system users to be serviced by the network. What then must be done is to use more AGC amplifiers than are necessary just to insure that amplifier AGC circuitry can "track" over the expected range of system level variations. This is illustrated as follows. Suppose to insure that signal levels will vary no more than ±4.0 db. anywhere in the cable system, at least one of every three cable amplifiers user must have AGC circuitry. By using an AGC amplifier for every second amplifier that is cascaded, the maximum amount that signal levels can vary will be constrained to approximately 2.5 db. As a result, the system now would require only a

5 db. tolerance, rather than an 8 db. tolerance, be maintained. More amplifiers could be cascaded without causing excessive signal distortion; this would require, however, the added cost of using more relatively expensive AGC amplifiers. In an actual cable design, the added cost of using more AGC amplifiers would be balanced against using low attenuation, higher priced coaxial cable requiring fewer amplifiers to be cascaded, and the cheaper alternative would be chosen.

We can now determine the minimum number of AGC amplifiers that will be required for the forward and reverse cable channels and for aerial and underground cable construction. Allowing ±0.5 db. signal variation to account for imperfect automatic gain control per amplifier, it can be seen that AGC amplifiers should be placed so that signal levels cannot vary more than ±3.5 db. between them.

The effects of temperature on signal level variation can be determined as follows. Page (7) suggests that CATV systems by designed to operate over a temperature variation of ±85° F. from some median temperature. (Presumably this 170° F. temperature variation applies only to aerial construction; for underground construction at a depth of four feet, temperature varies only ±20° F. from the local mean temperature.) (1) We will assume, however, that an aerially installed system in the St. Louis area need operate only through ±70° F. temperature variations; that is, the system will be designed to operate acceptably from -10° F. to 130° F.* Assuming that all underground construction places cables at least 18 inches below ground, underground portions of the system are designed to operate at temperatures of 56° F.

---

*The recorded temperature extremes for the St. Louis area are -11° F. and 106° F., while the average median temperature is 56° F. (8) The upper temperature limit of 130° used in the aerial system design is intended to include the effects of any additional heating caused by direct exposure to sunlight.

For a cable attenuation variation of one percent per 10° F., the ±70° F. temperature variation that the aerially constructed portions of the system are expected to experience is equivalent to a signal level variation of ±1.68 db. between amplifiers spaced 24 db. apart. In underground portions of the system, a ±50° F. temperature variation corresponds to a signal level variation of ±1.2 db. between amplifiers spaced 24 db. apart along the cable. Allowing ±0.5 db. per amplifier to account for amplifier gain changes due to aging and imperfect gain control, the possible signal level variations that can occur for different use of AGC amplifiers in aerial and underground portions of the system are listed in Table 5.1.1.

Table 5.1.1 lists the range of possible signal level variations that can occur for aerial and underground construction using different combinations of manual gain and automatic gain control amplifiers. It assumes that the level variation at the output of an AGC amplifier is within ±0.5 db. of the desired level, regardless of the level of the amplifier's input signal. In this way, we can see that for aerial construction, if AGC amplifiers are alternated with manual gain amplifiers, a maximum signal level variation of ±4.36 db. can occur between the AGC amplifiers in the cascade. Because the input circuitry of the AGC amplifiers can only compensate for input signal levels ±4.0 db. from the desired signal level, it is obvious that in aerial construction, AGC amplifiers must be used exclusively if signal level variations are to be controlled. Furthermore, aerial portions of the network using AGC amplifiers exclusively will need a minimum tolerance

Table 5.1.1: Summary Of Expected Level Variations As A Function of Component Selection And Construction Type

	Signal Level Variation (db.)					
	AGC amplifier		1st manual amplifier		2nd manual amplifier	
	Input	Output	Input	Output	Input	Output
Forward Aerial Construction:						
AGC amplifiers used exclusively	±2.18	±0.5	---	---	---	---
AGC amplifiers alternated with manual gain amplifiers	±4.36	±0.5	±2.18	±2.68	---	---
Forward Underground Construction:						
AGC amplifiers alternated with manual gain amplifiers	±2.7	±0.5	±1.7	±2.2	---	---
AGC amplfiers used at every third amplifier in cascade	±4.4	±0.5	±1.7	±2.2	±2.7	±3.2

NOTES:
a) AGC amplifier output level is controlled only for input variations of ±4 db.
b) Signal level variations are for 24 db. interamplifier spacing.
c) Aerially constructed portions of the system are expected to experience temperature variations of ±70° F. from median temperature.
d) Underground portions of the system are expected to experience temperature variations of ±50° F. from median temperature.

of 4.36 db. (±2.18 db.) to ensure that all of the network's users will receive signals of acceptable quality.

Similarly, Table 5.1.1 shows that in underground construction, AGC amplifiers can be alternated with manual gain amplifiers without allowing excessive signal level variation to occur. If AGC amplifiers, on the other hand, are only used for every third amplifier in cascade, excessive signal level variation can occur. Alternating AGC and manual gain amplifiers in underground portions of the system, a maximum signal level variation of ±2.7 db. is possible; therefore, those portions of the network would require a minimum tolerance of 5.4 db. Examination of Table 5.1.1 also shows that if AGC amplifiers are used exclusively in underground portions of the network, signal level variations of up to ±1.7 db. occur; thus, underground portions of the network built using AGC amplifiers exclusively require a tolerance of 3.4 db. This shows the tolerance required in a cable network can be reduced by using more AGC amplifiers than is absolutely necessary. By controlling signal levels more often, the required tolerance is reduced; this allows more amplifiers to be cascaded than could otherwise be done.

Similar calculations can be made to determine how often AGC amplifiers must be used in the return channels of the network for aerial and underground construction. Because the return channels occupy a bandwidth from five to thirty MHz, rather than the fifty to three hundred MHz bandwidth of forward channels, the amount of attenuation return signals receive is much less than the attenuation given forward signals. 24 db. interamplifier spacing at 300 MHz corresponds to 7.59 db. interamplifier spacing at thirty MHz; thus, a ±70° F. temperature variation corresponds to a signal level variation of ±0.53 db. at thirty MHz. Similarly, a ±50° F. temperature variation corresponds to a signal level variation of ±0.38 db. at thirty MHz. Table 5.2.3 states that for an input level variation of ±3.0 db., the return AGC amplifiers used will constrain output signal levels to within ±0.2 db. of the desired level. We assume in this design, however, that due to amplifier aging, the output signal level of the return AGC amplifiers will be constrained to within ±0.3 db. of the desired level; similarly, we assume that the manual gain amplifiers used can experience gain variations of up to ±0.3 db. due to amplifier aging. Under these assumptions, every third return amplifier cascaded in the aerial portions of the network must have AGC; in underground portions of the network, at least every fourth return amplifier cascaded must have AGC.

We have discussed how signal power level and the number of amplifiers in a cascaded amplifier system affect system performance. Similarly, we have discussed system tolerance and the method by which the required system tolerance is computed. Before the use of these factors is demonstrated in the design of one of the sample networks for the St. Louis metropolitan area, however, we must examine the effect that the highest frequency signal to be carried on the cable network has on the network's design.

As discussed previously, the signal attenuation of coaxial cable per unit length is directly proportional to the square root of the signal's frequency; (1) specifically, for a given type of coaxial cable, signal attenuation per unit length equals $K\sqrt{f}$ db., where K is a constant characterizing the particular coaxial cable considered and f is the signal frequency measured in MHz. As a result, the amplifiers used to compensate for the cable's attenuation do not have a flat passband response; rather, their passbands are shaped so that signals having lower carrier freuqencies receive less attenuation than do those with higher carrier frequencies. For example, an amplifier giving 24 db. amplification to 300 MHz signals would have a passband whose signal amplification as a function of frequency was $1.38\sqrt{f}$ db., where f is the signal's carrier frequency in MHz over the amplifier's passband, such as from fifty to three hundred MHz in the case of the forward cable amplifiers used here. Thus, 300 MHz signals would receive 24 db. amplification, while 50 MHz signals would receive only 9.8 db. amplification at each amplifier.

Because the tilt (i.e., shape) of each amplifier's passband can be adjusted during installation, the overall frequency response of the cable system normally needn't be considered during system design. Cable system design is affected, however, by the highest frequency to be carried on the cable network. Because the cable's attenuation is dependent upon the frequencies of the signals being carried, it follows that the highest frequency signals carried on the network will receive the most attenuation. In addition, the interamplifier spacing used will be dependent upon the maximum attenuation given any of the signals carried. As a result, the highest frequency carried on the network determines how closely repeater amplifiers must be spaced. And because only a limited number of amplifiers may be cascaded without causing excessive signal degradation, the highest frequency carried throughout the network determines the maximum distance over which a user may be serviced.

Table 5.2.3 lists the 24 db. interamplifier spacings at 300 MHz for the different types of coaxial cable used to construct the system. At 55° F., the 24 db. interamplifier spacing at 300 MHz for 0.75 inch styrenefoam dielectric coaxial cable is 0.528 miles. If it were found that no more than thirty amplifiers could be cascaded without causing excessive signal degradation, the cable system can service users located no more than 15.84 miles from the headend if a full fifty to three hundred MHz bandwidth is to be delivered to all system users. If the cable system were to serve a very large metropolitan area, on the other hand, the 15.84 mile radius might be insufficient. In that case, a compromise between the number of channels delivered to all the users of the cable network and the most distant user able to be served by the network can be made.

Assume that the most distant user to be reached by the network is located 17.5 miles from the system headend. Using 0.75 inch styrenefoam coaxial cable, 24 db. interamplifier spacing at 300 MHz is .528 miles while at 220 MHz, 24 db. interamplifier spacing is .528 ($\sqrt{300/220}$) miles or .617 miles. If the distant users need only receive channels having frequencies up to 220 MHz, then the system might be designed so that the cable carries signals having frequencies up to 300 MHz through the first fifteen repeater amplifiers; these fifteen amplifiers would be spaced .528 miles apart. Past the sixteenth cascaded amplifier, however, only signals having frequencies less than 220 MHz would be propagated; thus, these fifteen amplifiers could be spaced .618 miles apart. System users within 8.45 miles of the system headend would enjoy the use of forward cable bandwidth up to 300 MHz. Users located from 8.45 to 17.7 cable miles from the headend, on the other hand, would only be able to receive signals having carrier frequencies of up to 220 MHz. Thus, the distance over which a cable system can operate can be extended if the cable bandwidth available to all system users can be reduced. To cover really large distances, however, requires severe reduction in the highest frequency carried by the cable network.

5.1.3 A Coaxial Cable Network Design Example

5.1.3.1 Introduction

We have now considered all of the technical factors needed to make an initial design of a dedicated coaxial cable network. Using this information, the network designer can determine the types of coaxial cable and numbers of amplifiers required to service a particular area. Using the network component and construction cost estimates given in Appendix 5.2, therefore, the network designer should be able to make network cost estimates as a function of the different types of coaxial cable that might be used in building the network, and should be able to determine the type of coax resulting in the least expensive network. This Appendix. when used in conjunction with the information of Appendix 5.2, constitutes a useful tool for the designer of dedicated coaxial cable networks.

The remainder of this Appendix will illustrate the method by which the performance of a cascaded amplifier, coaxial cable transmission system can be verified. Using the design equations given in this Appendix with the amplifier specifications given in Table 5.2.3, we will examine the conditions under which maximum signal degradation occurs and we will verify that under these worst case conditions, signals will be able to be received with acceptable quality. In addition, we will discuss the technical requirements of a digital return network as opposed to a network allowing return video transmission to any point in the network. An analysis of all of the networks presented in Chapter 2 will not be undertaken; besides being excessively long, it is felt that such an analysis is of marginal interest. Sufficient data is given in this Appendix and Appendix 5.2, however, to allow the interested reader to verify that the networks presented would operate satisfactorily while resulting in the least possible network cost.

5.1.3.2 Designing The Return Video Network

In the return video network, video programming originated anywhere in the network, transmitted through the cable system's return channels to the headend, and from the headend, distributed over the network to all users should be received with acceptable quality. The received signals should have a minimum signal-to-noise ratio of 43 db., a maximum of -51 db. cross-modulation relative to 100% cross-modulation, and should be received at signal levels over 0 dBmV. To insure that signals could be received with acceptable quality at any point of the network, we must examine the two worst propagation paths existing in the network.

These two paths are the longest paths over which signals might be required to travel through all aerial and all underground cable construction, respectively. Making an initial assumption that all of the network's aerial construction will be done using the type of cable resulting in the least possible aerial network cost, and that all of the network's underground cable construction will be done using the type of cable resulting in the least possible underground network cost, one of these paths will require signals to pass through the largest return and forward amplifier cascade existing in the network. If the signals, having passed through the largest cascade, can be received with acceptable quality, it follows that video programming originated anywhere in the network will be able to be received at any other point in the network with acceptable quality. If, on the other hand, signals received over the worst case propagation paths cannot be received with acceptable quality, the network designer will either be required to use a different type of coaxial cable for parts of the network, or the number of channels delivered to all of the network's users will have to be reduced. The maximum return and forward amplifier cascade length can be reduced using either method.

Because digital signals are less vulnerable to degradation due to noise and distortion, a network allowing video programming to be originated at any point in the network will also allow digital signals to be transmitted from any point in the network. Thus, we do not have to consider the transmission of digital signals while designing the return video network. The effects of noise and distortion on digital signal reception will be discussed later.

The aerial construction worst case propagation path is located in the network's spoke four (see Figure 3 in text). A signal originated at the most distant point in spoke four and then received over the network's forward channels at the most distant point in spoke four would be required to pass in both directions through 14.4 miles of aerial cable construction. Assuming that all of the network's spoke three (see Figure 2 in text) was built using underground construction, the underground worst case propagation path would be traveled by a signal originated by spoke three's most distant user and then received on the network's forward channels by spoke three's most distant user. The signal would be required to pass in both directions through 10.27 miles of underground cable construction.

In determining the type of cable resulting in the least cost for aerial portions of the cable network, several factors have to be considered. First, it should be remembered that if signal levels are to be controlled over the range of temperature variations the aerial portions of the network will experience, AGC amplifiers will have to be used exclusively for the network's forward channels. Because AGC amplifiers are more expensive than manual gain amplifiers, total aerial network cost might be reduced by using a large diameter, low loss cable in aerial portions of the network. In addition, Table 5.2.6 indicates that the cost of installing aerial portions of the network is independent of the size of the cable to be installed. As a result of these two factors, it can be shown that the cost per mile of aerial portions of the network is minimized if .75 inch styrenefoam dielectric coaxial cable is used.

Using .75 inch styrenefoam dielectric coaxial cable, 24 db. interamplifier spacing at 55° F. for 300 MHz signals is .528 miles. Thus, signals originated and then received at the most distant point in spoke four will be required to pass through twenty-seven return amplifiers, the headend, and twenty-seven forward cable amplifiers. All forward amplifiers used plus the headend will have automatic gain control circuitry, while one-third of the return amplifiers used will have automatic gain control circuitry. With this information, plus the specifications of the amplifiers given in Table 5.2.3, we can determine if signals will be excessively degraded over the worst case aerial propagation path.

Equations 5.1.4, 5.1.5, and 5.1.8 allow us to determine the minimum signal level that can be acceptably propagated through a cascaded amplifier system. For convenience, equation 5.1.4, which determines the noise factor of an N+1 amplifier cascade, is repeated below.

$$f_{1:2N+1} = f_1 + \sum_{i=1}^{N}\left[\frac{f_{2i+1}}{\prod_{j=1}^{2i} g_j}\right] - \sum_{i=1}^{N}\left[\prod_{j=1}^{2i-1} g_j\right]^{-1}. \qquad [5.1.4]$$

Terms of the form $\prod_{j=1}^{2i} g_j$ represent the gain of the cascade measured at the input of the (i+1)th amplifier, while terms of the form $\prod_{j=1}^{2i-1} g_j$ represent the gain of the cascade measured at the output of the (i)th amplifier. Cascade gain measured at the input of an amplifier is equal to the amount of signal level variation present at that point in the cascade, while cascade gain measured at the output of an amplifier is equal to the amplifier's nominal gain plus the amount of signal level variation occuring at that point in the cascade.

By examining the terms of equation 5.1.4, we can determine under what conditions cascade noise factor will be maximized. The individual noise factors of the amplifiers used can be assumed to be constant over the range of signal levels used in cable transmission systems. The cascade gain at the inputs and the outputs of the amplifiers used, on the other hand, are influenced by the environment in which the system is operating and will greatly affect the cascade's noise factor. Cascade gain at the input of the amplifiers ($\prod_{j=1}^{2i} g_j$) will be on the order of unity, while cascade gain at the output of the amplifiers ($\prod_{j=1}^{2i-1} g_j$) will be on the order of ten and one hundred for return and forward amplifiers respectively. Therefore, examination of equation 5.1.4 shows that cascade noise factor will be maximized when the gains measured throughout the system are minimal.

Every third return amplifier cascaded will have AGC. Assuming that signal levels are constrained to within ±0.3 db. at the output of a return AGC amplifier, while the manual return amplifiers can experience gain variations of ±0.3 db., the range of signal level variations possible at the inputs and outputs of the first manual return amplifier, second manual return amplifier, and the AGC return amplifier cascaded are given below.

	1st man. amp.	2nd man. amp.	AGC amp.
Input Level Variation	±0.83 db.	±1.66 db.	±2.49 db.
Output Level Variation	±1.13 db.	±1.96 db.	±0.30 db.

The nominal gain of the return amplifiers is 7.59 db., and the noise figure of the return amplifiers is 9 db. Converting these specifications from decibel to linear notation and using equation 5.1.4, it can be seen that the worst case noise factor for the twenty-seven aerially cascaded return amplifiers is given by

$$f^{wc}_{ret} = 7.94 + 7.94\left[\frac{8}{.826} + \frac{9}{.682} + \frac{9}{.563}\right] - \left[\frac{9}{4.43} + \frac{9}{3.66} + \frac{8}{5.36}\right] = 310.6 \ . \qquad [5.1.22]$$

We will assume that the headend equipment required to transfer programming from the return to the forward channels has an eight db. noise figure, and gain and signal level variation control properties similar to those of a forward AGC cable amplifier. The specifications of the forward cable amplifiers used are given in Table 5.2.3, while the possible signal level variations for an aerially installed forward cable system using AGC amplifiers exclusively are given in Table 5.1.1. Using this information in equation 5.1.4, it can be seen that the worst case noise figure for the cascade consisting of the headend signal processing equipment and the twenty-seven cascaded AGC amplifiers is given by

$$f_{fwd}^{wc} = 6.31 + \frac{6.31 \times 27}{.606} - \frac{27}{224} = 287.3 \quad . \qquad [5.1.23]$$

The total worst case noise factor for the aerial system can be determined using equation 5.1.3. The cable's return amplifier cascade is considered to be the first device being cascaded; its worst case noise factor is shown in equation 5.1.22 to be 310.6 with a corresponding (linear) gain of 5.36. The second device being cascaded is the length of cable connecting the output of the last return amplifier to the headend; its worst case noise factor is 6.49 with a corresponding (linear) gain of 224 (23.5 db.). Using this information with equation 5.1.3, the worst case noise factor for the aerial cable system is given by

$$f_{tot}^{wc} = 310.6 + \frac{5.49}{5.36} + \frac{286.3}{.825} = 658.7 \quad . \qquad [5.1.24]$$

Thus, the aerial system's worst case noise figure is 28.2 db.; using equation 5.1.8, the minimum signal level ensuring that received signals will not be excessively degraded due to noise under worst case conditions is given by

$$S(min) = -59.2 + 22.7 + 28.2 + 43 \text{ dBmV}. \qquad [5.1.25]$$

This value of S(min) corresponds to the minimum allowable signal level at the output of the cascade's forward amplifiers; the corresponding minimum signal level at the output of the cascade's return amplifiers would be nominally sixteen db. less. Under worst case noise conditions, the overall gain of the entire cascade is 22.7 db.

Before considering the maximum signal levels able to be carried on the cascade under worst case distortion conditions, one final observation concerning S(min) can be made. Since the minimum signal level allowed at the output of the forward cable amplifiers is 34.7 dBmV, it follows that the minimum signal level existing anywhere in the forward cascade is 11.2 dBmV. This minimum cascade signal level occurs at the inputs to the forward amplifiers under worst case noise conditions. Delivering signals to users at levels greater than the required 0 dBmV, therefore, will be possible under worst case noise conditions.

We now determine the maximum signal levels able to be carried on the cascade under worst case distortion conditions. By first determining the amount of distortion generated at an arbitrary signal level, the signal level at which -51 db. distortion will be generated can then be computed. This is the maximum signal level able to be carried on the network.

Table 5.2.3 shows that the forward amplifiers used in the cascade each generate -89 db. distortion when carrying 35 channels at an output level of 35 dBmV. Assuming the system is designed to operate at forward amplifier output levels of 35 dBmV, imperfect level control would allow forward amplifier signal levels of up to 35.5 dBmV to occur; each forward amplifier would then generate -88 db. distortion. Because each amplifier and the headend equipment are operating under identical conditions, computation of the total distortion generated by the cascade's twenty-seven forward amplifiers and the headend equipment under worst case conditions is straightforward. Referring to equation 5.1.13,

$$\mathrm{XM(db.)}_{\mathrm{fwd}}^{\mathrm{wc}} = -88 + 20 \log_{10} 28 = -59.1 \text{ db.} \qquad [5.1.26]$$

The amplifiers used in the return signal portion of the network, however, do not operate under identical conditions. Since AGC amplifiers are used only for every third amplifier in the return signal cascade, under worst case conditions the maximum signal level possible at each amplifier is determined by the amplifier's position in the cascade. As a result, calculating the distortion generated under worst case conditions by the return amplifiers in the cascade requires that each amplifier's contribution to the distortion generated be determined. These individual amplifier distortions can then be totaled, and their sum converted to decibels with respect to one hundred percent cross-modulation distortion.

If the cascade's forward amplifiers are designed to operate at a signal output level of 35 dBmV, the corresponding return amplifier signal output level is 18.6 dBmV. Therefore, imperfect signal level control would allow the output levels of the return AGC amplifiers used to reach 18.9 dBmV. Similarly, the output level of the manual gain amplifier following an AGC return amplifier in cascade could be as high as 19.7 dBmV and the output level of the second manual gain return amplifier following an AGC return amplifier in cascade could reach 20.6 dBmV.

Referring to Table 5.2.3, the return amplifiers each generate -92 db. cross-modulation distortion when carrying three channels at an output level of 34 dBmV. Thus, each of the nine cascaded return AGC amplifiers would generate -122.2 db. cross-modulation distortion, which corresponds to 7.75 x 10^{-5} percent cross-modulation distortion generated per return AGC amplifier. Each manual gain amplifier following an AGC amplifier in cascade could generate up to -120.6 db. distortion, corresponding to 9.35 x 10^{-5} percent cross-modulation distortion generated per amplifier. Finally, under worst case distortion conditions, each second manual gain return amplifier following a return AGC amplifier in cascade could generate up to -118.8 db. distortion; this corresponds to 1.15×10^{-4} percent cross-modulation distortion generated per amplifier.

Nine of each type of return amplifier will be in the return amplifier cascade. Therefore, the total percentage of cross-modulation distortion generated by the return amplifiers under worst case distortion conditions is given by

$$\%\ XM = 9(7.75 \times 10^{-5} + 9.35 \times 10^{-5} + 1.15 \times 10^{-4}). \qquad [5.1.27]$$

The total percentage cross-modulation generated by the return amplifiers under worst case conditions is 2.57×10^{-3} percent. This corresponds to -91.8 db. cross-modulation distortion.

We have shown that if the cascade is designed to operate at a forward amplifier signal output level of 35 dBmV, the cascade's forward amplifiers can generate up to -59.1 db. distortion, while the cascade's return amplifiers can generate up to -91.8 db. cross-modulation distortion. Converting each of these figures to percentage distortion with respect to one hundred percent distortion, it can be shown that the maximum distortion generated by the cascade, assuming the cascade is designed to operate with a forward amplifier signal output level of 35 dBmV, is 0.113 percent, which is equivalent to -58.9 db. cross-modulation distortion.

We previously stated that a maximum of -51 db. cross-modulation distortion could be generated by the cascade without causing excessive signal degradation. The cascade generates -58.9 db. distortion under worst case conditions when designed to operate at a forward amplifier signal output level of 35 dBmV. By considering the effect that increasing the cascade signal level will have upon the amount of distortion generated, we will be able to compute S(max), the forward amplifier signal output level causing a total distortion of -51 db. to be generated.

Because different amounts of signal level variation are possible at different points in the cascade, the amount of distortion generated by a particular amplifier under worst case conditions is dependent upon the amplifier's cascade position. We previously noted that the amount of distortion generated by each amplifier will increase two db. for each one db. increase in output signal level. Thus, an increase in cascade signal level would affect the amount of distortion generated if relative signal levels at the inputs and the outputs of the cascade's amplifiers remain fixed. An increase in the cascade signal level would not, however, affect the amount of signal level variation occuring at the inputs and outputs of the cascade's amplifiers; therefore, the amount of additional distortion generated due to signal level variations in the system under normal operating conditions is independent of the cascade's design signal level. The total distortion generated by any cascaded amplifier system will increase two db. for each one db. increase in cascade signal level. Thus, the cascade signal level at which -51 db. cross-modulation distortion will be generated under worst case distortion conditions is

$$S(\max) = 35 + \frac{(-51 - (-58.9))}{2} = 38.95 \text{ dBmV.} \qquad [5.1.28]$$

Consider now the relation of S(min) given in equation 5.1.25 with S(max) as given in equation 5.1.28. S(min), which in this example is 34.7 dBmV, is the minimum forward amplifier signal output level for which the system should be designed to operate if signals are not to be excessively degraded by noise at any time. S(max), on the other hand, is the maximum forward amplifier signal output level for which the system should be designed to operate if signals are not to be excessively degraded by distortion at any time. Because 38.95 dBmV, the value of S(max), is greater than the value of S(min) by 4.25 db., it follows that the aerial cascaded amplifier system we have examined allows signal level variation of ±2.13 db. from the cascade's optimum signal level, in addition to any level variations caused by temperature variations and amplifier aging, before excessive signal degradation can occur. Because under worst case conditions, S(max) is greater than S(min), the cascade will be able to distribute signals under all conditions without generating excessive noise or distortion.

It should be noted that, in this case, the 4.25 db. margin between the values of S(max) and S(min) is not the tolerance of the system. The concept of a system's tolerance, (3) as was discussed earlier in conjunction with equations 5.1.19 and 5.1.20, is useful in illustrating the effect of adding additional amplifiers to a cable system. It assumes, however, that all of the cascaded amplifiers are identical; in addition, it assumes that all of the cascaded amplifiers operate under the same conditions, and therefore will each generate identical amounts of noise and distortion. Under these assumptions, S(min) is defined to be the minimum cascade signal level allowing signals to be propagated without excessive noise degradation, while S(max) is defined to be the maximum cascade signal level allowing signals to be propagated without excessive degradation due to distortion. Tolerance is the difference between S(max) and S(min) determined under these assumptions.

In our bidirectional cable system, on the other hand, we have seen that three types of amplifiers (forward AGC, return AGC, and manual gain return amplifiers) were cascaded. In addition, different amounts of of signal level variation were possible for each type of amplifier. As a result, there are no well defined signal levels at which excessive noise and distortion are generated, making the system's "tolerance" meaningless.

Instead, we computed the minimum and maximum signal levels between which the system should be designed to operate. If signal levels were set between S(min) and S(max) under "zero-variance" conditions, the designer insured that under worst case conditions, signals could be propagated without excessive noise or distortion interference being generated. There is no straightforward procedure allowing the number of additional amplifiers that may be cascaded without causing excessive signal degradation under any conditions to be determined for networks utilizing several amplifier types.

We have shown that for the video return network, aerial sections should be built using .75 inch styrenefoam cable, using forward AGC amplifiers exclusively and using an AGC amplifier for every third amplifier in cascade. Similarly, it can be shown that the least expensive return video network results if underground portions of the network are built using .5 inch styrenefoam coax, using forward AGC amplifiers exclusively and using an AGC amplifier for every third return amplifier in cascade.

First, users of the network can receive video programming. In the digital return network, however, video programming can be originated only from the headend; thus, video signals originated at the system headend and propagated only through the system's forward amplifiers must be able to be received with acceptable quality by the system's users. As was the case for the video return network options, received video signals are to have a minimum signal-to-noise ratio of 43 db., no more than -51 db. total cross-modulation distortion, and should be received at a signal level greater than 0 dBmV.

Unlike video signals, however, digital signals may be originated from any point in the digital return network option. As a result, a digital signal traveling both through the network's return and forward cable amplifiers must not be excessively degraded. In this section, we will discuss the effects of cascade-generated noise and distortion upon the reception quality of digital signals.

The effect of noise and distortion on the reception of digital signals is to mask the signal transmitted from the information source. In on-off keying, for example, the random variations of the noise generated in the cable system could combine subtractively with a pulse transmitted over the network. As a result, it would appear to the receiver that no pulse had been transmitted and the receiver would indicate that a binary "0", rather than a "1", was received. On the other hand, if a burst of random noise occurred during an interval when a pulse had not been transmitted, it would appear that a pulse had been transmitted and the receiver would indicate that a binary "1", rather than a "0", had been received. In either case, one bit error would have been made.

The criterion by which the quality of digital signal transmissions are judged is the probability that an error will occur. Using a coaxial cable channel and a Network Interface Unit to deliver data from the PLATO IV central computer to 1008 student terminals, for example, probabilities of error on the order of 10^{-6} are realized. (9) Since data is transmitted from the central computer at a rate of 1.2096×10^{6} bits per second, the mean rate at which bit errors will be made is on the order of twelve per ten seconds. This is acceptable for a system such as PLATO IV; a system user normally would not notice whether a single point in his terminal's plasma panel display had wrongly been lit or extinguished. In transmitting other types of digital data, on the other hand, a channel resulting in a probability of error of 10^{-6} might cause an unacceptable number of errors to be made. Such a system would require that a higher quality channel resulting in a lower probability of error be used.

Because the statistical description of the nonlinear distortion generated in a cable system is not similar to the description of the thermal noise generated in the system, the effects of distortion on mean probability of error in digital signal transmissions can be different from the effects of noise. In the case of a network carrying synchronous video programming, digital signals would be regularly compressed in amplitude at intervals corresponding to the times the video programming's sync pulses were being transmitted. If the digital signals were being transmitted using a form of amplitude modulation, during these intervals, it is reasonable to expect that bit errors would be more likely to occur. Experience with broadband cable systems carrying many independent channels of programming, however, has shown that the effects of distortion can be likened to the effects that an additional amount of random noise would have on the received signal's probability of error. (1) We will assume that the digital return networks being designed carry mostly nonsynchronous video programming and that the effect of the nonlinear distortion generated in the networks will be to increase the effective amount of noise interference that must be overcome.

The minimum signal-to-noise ratio allowed video signals received through the digital return network's forward channels is 43 db.; that is, the level of noise generated by the forward amplifers must be at least 43 db. below the level at which signals are carried through the cascade. Digital signals originated other than at the headend, however, would also be propagated through one spoke's return amplifiers and would receive additional degradation in the return amplifiers. In the course of this work, it was found that if the minimum number of return AGC amplifiers required to control signal level variations were used in the digital return networks (this corresponds to at least every third return amplifier used in aerial portions of the network, and every fourth return amplifier used in underground portions of the network), excessive noise would be generated. For example, if we conservatively assume that the return cascade generates up to three times as much noise as does the forward cascade, the resulting minimum signal-to-noise ratio of digital signals propagated through both the forward and return cascades would be on the order of 37 db.

Additional interference would be generated by the cascades in the form of nonlinear distortion. In the forward cascade, for example, -51 db. cross-modulation distortion is allowable. But compared to the thermal noise generated in the cascades, this additional interference would have little effect; we can estimate that it would lower the minimum signal-to-noise ratio of received digital signals a further two db., resulting in received digital signals having an effective signal-to-noise ratio of 35 db. And because signals are propagated at relatively low levels in the return cascade while the return cascade's bandwidth does not allow a great number of signals to be carried (compared to the forward cascade), the distortion generated in the return cascade is insignificant and for the purposes of this discussion can be ignored.

The mathematical relationships between a channel's signal-to-noise ratio and the signal probability of error that will result if a particular type of modulation technique is used are described in many available communications theory texts. (2, 10) One type of modulation technique that might be used on the dedicated networks, m-level amplitude shift keying (m-ary ASK), illustrates the digital signal reception quality that can be expected from a network able to distribute video signals of acceptable quality from the headend and in which only the minimum number of AGC amplifiers required to control signal level variations have been used.

Assuming the network will distribute digital signals originated at any point in the network to any other point in the network with a minimum signal-to-noise ratio of 35 db., if m-ary ASK is the modulation technique used, signals having up to eight levels (i.e., $2 \leq m \leq 8$) can be received with error probabilities of less than 10^{-16}. (1) If the signal level at which the digital signals are carried on the network is reduced, or if other types of modulation techniques are used, similar acceptably low probabilities of error should result.

As a result of this fact, a general conclusion can be made. In the design of a digital return network, the principal factor affecting the network design is the amount of degradation signals will receive in the forward cascade. If video signals may be distributed from the headend without being excessively degraded, and if the minimum number of AGC amplifiers required to control signal level variations is used in the return cascade, digital signal transmission with acceptably low probabilities of error will be possible. As a result, the forward cascades of the digital return networks presented in Chapter 2 were designed to be able to acceptably distribute video programming from the headend. The return cascades, on the other hand, use the minimum number of AGC amplifiers required (at least every third amplifier in aerial portions of the network, and at least every fourth amplifier in underground portions of the network) to control signal level variations. These were the criteria used in the design of the digital return networks presented in Chapter 6.

APPENDIX 5.1 BIBLIOGRAPHY

1. Members of the Technical Staff, Transmission Systems For Communication, Fourth Edition, Bell Telephone Laboratories, 1970.

2. Taub, H. and Schilling, D., Principles of Communications Systems, McGraw-Hill, 1971.

3. Simons, K., Technical Handbook For CATV Systems, Third Edition, Jerrold Electronics Corporation, 1968.

4. Dean, C. E., "Measurements of the Subjective Effects of Interference in Television Reception", Proceedings of the IEEE, Vol. 48, June 1960, pp. 1035-1049.

5. Switzer, I., "A Harmonically Related Carrier System for Cable Television", IEEE Transactions On Communications, Vol. COM-23, No. 1, Jan. 1975, pp. 155-166.

6. Palmer, J. R., "CATV Systems---Design Philospphy and Performance Criteria as the Basis for Specifying Equipment Components", IEEE Transactions On Broadcasting, Vol. BC-13, No. 2, April 1967, pp. 57-67.

7. Page, O. D., "CATV Transmission System Design for Reliable Year-Round Operation", IEEE Transactions On Broadcasting, Vol. BC-15, No. 4, December 1969, pp.80-88.

8. 1975 World Almanac & Book of Facts, Newspaper Enterprises Association, 1974, pp. 245-247.

APPENDIX 5.2

SPECIFICATIONS OF THE COMPONENTS USED IN DESIGNING THE EXAMPLE NETWORKS

As discussed previously, there are several factors that influence the design of a practical dedicated coaxial cable network. Among these are the cable's attenuation, the amount of noise and distortion generated in the amplifiers, and the range of temperatures over which the network is expected to operate acceptably. Equally important in the decision of which components and techniques will be used is the resulting system cost; usually, the system chosen is one meeting the signal quality specifications as cheaply as possible. To aid the interested reader in understanding the design of the networks presented in Chapter 2, network component specifications and costs will be briefly presented here. Thus, the interested reader can verify that the proposed networks not only meet signal quality specifications but also meet them as inexpensively as possible. This fact can be proven by substituting different cable types in the network and noting the effect on total system cost and performance.

Coaxial cables that might be used in the distribution system of the dedicated network are available in three sizes and with two types of dielectric. Table 5.2.1 lists the maximum attenuation each type of cable gives a 300 MHz signal and a 30 MHz signal at a temperature of 55° F., the average median temperature for the St. Louis area. (1) The resulting 24 db. interamplifier spacing for each type of cable is listed in Table 5.2.2.

Table 5.2.1: Signal Attenuation as a Function of Cable Size and Dielectric (2, 3)

Maximum loss per 100 ft. at 55° F., 300/30 MHz

Cable diameter	Polyfoam Dielectric	Styrenefoam Dielectric
0.412 in.	1.92/0.61 db.	1.60/0.51 db.
0.500 in.	1.60/0.51 db.	1.28/0.41 db.
0.750 in.	1.16/0.37 db.	0.86/0.27 db.

Table 5.2.2: 24 db. Interamplifier Spacing as a Function of Cable Size and Dielectric

24 db. amplifier spacing at 55° F., 300 MHz

Cable diameter	Polyfoam Dielectric	Styrenefoam Dielectric
0.412 in.	0.236 mi.	0.284 mi.
0.500 in.	0.284 mi.	0.375 mi.
0.750 in.	0.391 mi.	0.528 mi.

The performance specifications for typical amplifiers used for forward and reverse communications are listed in Table 5.2.3. Also listed in Table 5.2.3 are the AGC/ALC characteristics (where applicable) of the amplifiers. The system designs presented here assume that aerial portions of the network experience temperatures from -15 to 125° F., while underground portions of the network experience temperatures from 5 to 105° F., regardless of the installation method used.

The method by which the degree of AGC required in the network can be determined is discussed in Appendix 5.1. If one-half db. maximum signal level variation at a forward amplifier's output is allowed to account for imperfect gain control and amplifier aging, then AGC/ASC amplifiers must be used exclusively in aerial construction, while manual gain amplifiers may be alternated with AGC/ASC amplifiers in underground construction if these assumptions hold. Similarly, assuming 0.3 db. gain variation at the output of reverse amplifiers, at least one-third of the reverse amplifiers used in aerially constructed portions of the network must be AGC amplifiers, while one quarter of the amplifiers used for reverse communications in underground portions of the network must have AGC.

The following are the minimum acceptable video performance specifications for a signal received anywhere in the network:

Signal to noise ratio = 43 db. (NCTA)
Maximum allowable cross-modulation distortion = -51 db.
Minimum received signal level = 0 dBmV.

The signal-to-noise ratio is referenced to a 4 MHz noise bandwidth and is measured with respect to the level of signals' sync pulses. Similarly, cross-modulation distortion is measured with respect to

Table 5.2.3: Typical CATV Amplifier Performance Specifications (4)

Forward Trunk Amplifier Specifications:

Operating Bandwidth	50-300 MHz
Cross-modulation (at 24 db. gain, 35 channel operation)*	-89 db. at 35 dBmV
Second-order distortion	-79 db. at 35 dBmV
Third-order distortion	-98 db. at 35 dBmV
Typical Noise Figure (24 db. gain)*	8 db.
Automatic Level Compensation	± 0.25 db. Output Change for ± 4 db. Cable Change
Automatic Slope Compensation*	± 0.25 db. Output Change for 0-8 db. Cable Change

Reverse Trunk Amplifier Specifications:

Operating Bandwidth	6-30 MHz
Cross-modulation (at 14 db. gain, 3 channel operation)**	-92 db. at 34 dBmV
Second-order distortion	-79 db. at 34 dBmV
Third-order distortion	---
Typical Noise Figure (16 db. gain)**	9 db.
Tilt-compensated Automatic Control**	± 0.2 db. Output Change for ± 3 db. Cable Change

---

Notes: a) Automatic Level Compensation is the manufacturer's term for its forward amplifier AGC circuitry.

b) Tilt-compensated Automatic Control is the manufacturer's term for return amplifier fixed slope AGC circuitry.

---

*At 300 MHz.

**At 30 MHz.

sync level. By maintaining the received signal level above 0 dBmV, individual receiver noise figures should not noticeably affect the amount of noise discerned in received signals. (5)

Having listed the technical characteristics of the components that might be used in the construction of the dedicated network, their respective costs can be listed. The 1972 prices of the various types of coaxial cable that might be used are listed in Table 5.2.4. These prices are for cable purchased in quantities of forty miles or greater. The 1975 prices of amplifiers used in the system are listed in Table 5.2.5.

There are many types of miscellaneous equipment needed that also contribute to the final cost of the network's coaxial cable distribution system. Examples of this equipment include the components needed to connect users to the cable distribution system and the electronic equipment needed to interface programming originated at the various users' facilities and at the headend into the distribution system. Because this equipment does not comprise a significant portion of the total system cost, it is not to be discussed here in detail; readers wishing a detailed description of the equipment's cost are urged to consult Weinberg's report. (2) An estimate of miscellaneous equipment cost will be included in the system cost estimates given in Chapter 3 of the text.

Another factor contributing to total system cost is the cost of the methods used to install various sections of cable. Representative per mile costs for each of the three methods used, aerial construction, direct burial construction, and installation in existing conduits, are outlined in Tables 5.2.6, 5.2.7, and 5.2.8

Table 5.2.4: Typical 1972 Coaxial Prices (2)

	Cost per Mile	
Cable diameter and type	Polyfoam Dielectric	Styrenefoam Dielectric
0.412" Diameter		
Jacketed	$ 510.00	$ 581.00
Jacketed with Flooding Compound	551.00	611.00
Jacketed with Flooding and Armor	855.00	913.00
0.500" Diameter		
Jacketed	$ 681.00	$ 762.00
Jacketed with Flooding Compound	737.00	805.00
Jacketed with Flooding and Armor	1088.00	1214.00
0.750" Diameter		
Jacketed	$1295.00	$1500.00
Jacketed with Flooding Compound	1408.00	1535.00
Jacketed with Flooding and Armor	1890.00	2225.00

Note: Prices given are for quantities of forty or more miles of cable purchased.

Table 5.2 5: Typical 1975 Amplifier Costs (4)

Amplifier Type	Amplifier Cost
Trunk amplifier having manual gain control in both forward and reverse directions	$ 798
Trunk amplifier having AGC/ASC in forward direction, manual gain control in reverse direction	$ 926
Trunk amplifier having manual gain control in forward direction, AGC in reverse direction	$ 878
Trunk amplifier having AGC/ASC in forward direction and AGC in reverse direction	$1026
Trunk amplifier having manual gain control in both directions and having bridging capabilities	$1183
Trunk amplifier having AGC/ASC in forward direction, manual gain control in reverse direction, and having bridging capabilities	$1311
Trunk amplifier having manual gain control in forward direction, AGC in reverse direction, and having bridging facilities	$1263
Separate bridger amplifier	$ 784

Notes: a) The forward direction refers to signals being carried from the headend outward to the users; the reverse direction, on the other hand, refers to signals being carried from users back to the headend.

b) AGC refers to automatic gain control of an amplifier the shape of whose frequency response curve is fixed. AGC/ASC, on the other hand, refers to both automatic gain control and automatic control of the slope (shape of the frequency response curve) of the amplifier. For a discussion of the required frequency response of a coaxial cable repeater amplifier, see Appendix 5.1.

c) Bridger amplifiers are required whenever the cable network divides into two sections of cable of appreciable length.

Table 5.2.6: Typical Construction Costs (2)

Aerial Plant One Mile In Length (1972 prices)

For a Single Cable

Pole rearrangement cost (per mile)	$ 700
Hardware and parts cost (per mile)	400
Construction costs at $.25 per foot	1320
Technical supervision (per mile)	150
Electrical equipment installation and balance (per mile)	150
Miscellaneous engineering	150
TOTAL COST	$2870

For Second Cable Installed at Time of Initial Installation

Hardware and parts cost (per mile)	$ 400
Construction costs (15% of 1st construction cost)	198
Electrical equipment installation and balance (per mile)	150
Technical supervision	50
TOTAL COST	$ 798

Table 5.2.7: Typical Construction Costs (2)

Directly Buried Plant One Mile In Length (1972 Prices)

Per Mile Trenching, Back Filling, and Compacting Costs

Trenching (independent of depth up to 18" in clay or mixture of clay and sand, loam, topsoil, etc.)	$ 634
Hand Back Filling	1214
Compacting	1056
TOTAL PER MILE EXCAVATION COST	$2904

Per mile Direct Burial Cable Installation Costs

Cable diameter (assumes armored cable)	Per Mile Cost
0.412"	$1303
0.500"	1685
0.750"	2759

Resodding Cost Per Mile	$1214

Total per mile Construction Cost for First Cable

Cable diameter	Per Mile Cost*
0.412"	$5421
0.500"	5803
0.750"	6877

Total per mile Construction Cost for Second Cable

Cable diameter	Per Mile Cost**
0.412"	$1042
0.500"	1348
0.750"	2207

Note: 1) For a second cable add 80 percent.
2) Cost does not include the cost of the cable.
3) Add $104 amplifier installation, balancing, and pedestal installation cost for each amplifier in direct burial installation.

*Does not include cost of cable, add $104 for each amplifier installed for first cable.

**Does not include cost of second cable, add $29 for each amplifier installed and balanced in existing pedestal.

Table 5.2.8: Typical Construction Costs (2)

Cable Installed in Existing Conduit One Mile in Length (1972 prices)

Cable diameter (assumes flooding compound)	Per mile cost*
For first cable	
0.412"	$1533
0.500"	1839
0.750"	3066
For second cable installed at same time as first	
0.412"	$1226
0.500"	1471
0.750"	2452

---

*Add $29 for each amplifier installed and balanced in existing conduit.

respectively. It should be noted that in each case, substantial savings can be realized if multiple cables are installed simultaneously. Therefore, serious consideration should be given to installing a dedicated educational cable system at the same time an area is wired for conventional CATV. Similarly, if demand for cable services is expected to exceed the capacity of a single cable system in the near future, the possibility of initially installing a dual cable system and allowing the second cable to remain unused until it is needed should be seriously considered.

Finally, if network cables are mounted in utility conduits or on utility poles, a yearly rental fee will be charged. Assuming a charge of $6 to $7 per pole per year (regardless of the number of cables installed on the pole), (6) estimated pole rental fees will cost between $300 and $350 per year per aerial strand mile. A similar estimated rental fee for conduit installations is not available.

APPENDIX 5.2 BIBLIOGRAPHY

1. 1975 World Almanac and Book of Facts, Newspaper Enterprises Association, 1974, pp. 245-247.

2. Weinberg, G., Cost Analysis of CATV Components, RMC Incorporated, Bethesda, Maryland, June 1972. [NTIS No. PB 211 012]

3. Members of the Technical Staff, Transmission Systems for Communications, Bell Telephone Laboratories, Inc., Fourth Edition, 1970.

4. From manufacturers' product information.

5. Palmer, J. R., "CATV Systems -- Design Philosophy and Performance Criteria as a Basis for Specifying Equipment Components," IEEE TRANSACTIONS ON BROADCASTING, Vol. BC-13, No. 2, April 1967, pp. 57-67.

6. Telephone conversation with Mr. O. F. Hurst, Division Plant Engineer, Southwestern Bell Telephone Company, February 1975.

BIBLIOGRAPHY

1. Ballard, R. and L. F. Eastwood, 'Telecommunications Media For The Delivery of Educational Programming," Memorandum No. 75/1 Center for Development Technology, Washington University, St. Louis, Missouri.

2. Morley, R. and L. F. Eastwood, "Alternative Communication Designs For An Operational PLATO IV CAI System," Report No. CDTCG-R(T)-75/3, Center for Development Technology, Washington University, St. Louis, Missouri, August 1975.

3. Stifle, J., D. Bitzer, and M. Johnson, "Digital Data Transmission Via CATV," CERL Report X-26, May 1972, Computer-Based Education Research Laboratory, University of Illinois, Urbana, Illinois.

4. Simons, K., Technical Handbook for CATV Systems, Jerrold Electronics Corporation, Third Edition, 1968.

5. Page, O. D., "CATV Transmission System Design for Reliable Year-Round Operation," IEEE Transactions On Broadcasting, Vol. BC-15, No. 4, December 1969, pp. 80-88.

6. Barnett, H. J. and A. T. Denzau, "Future Development of Instructional Television," Memorandum 71/5, (43 pp), November, 1971 (with assistance from J. R. DuMolin and J. P. Singh), (ERIC No. 057 574) [NASA-CR-124700].

7. Telephone conversation with Mr. O. F. Hurst, Division Plant Engineer, Southwestern Bell Telephone Company, February 1975.

8. Johnson, L. L., et. al., Cable Communication In The Dayton Miami Valley: Basic Report, Rand Corporation, R-943 KF/FF, January 1972.

9. Weinberg, G., Cost Analysis of CATV Components, RMC Incorporated, Bethesda, Maryland, June 1972, [NTIS No. PB 211 012].

10. Members of the Technical Staff, Transmission Systems for Communications, Bell Telephone Laboratories, Inc., Fourth Edition, 1970.

11. Palmer, J. R., "CATV Systems -- Design Philosophy and Performance Criteria as a Basis for Specifying Equipment Components," IEEE Transactions On Broadcasting, Vol. BC-13, No. 2, April 1967, pp. 57-67.

12. Stetten, K. and J. Volk, Interactive Television: Volume I, Introduction and Interim Summary, M72-200, The MITRE Corporation, May 1973.

13. Alpert, D. and D. Skaperdas, "The Design of an Economically Viable Large-Scale Computer Based Education System," CERL Report X-5, July 1973, Computer-Based Education Research Laboratory, University of Illinois, Urbana, Illinois.

14. Bruns, Jr., W. J., Introduction To Accounting, Economic Measurements for Decisions, Addison-Wesley, 1971.

15. Martin-Vegue, Jr., C. A., et. al., "Technical and Economic Factors in University Instructional Television Systems," Proceedings of the IEEE, Vol. 59, No. 6, June 1971, pp. 946-953.

16. Malarkey, Taylor and Associates, "Pilot Projects for the Broadband Communications Distribution System," November 1971, Malarkey Taylor, and Associates, Washington.

17. Eller, T. and J. Volk, An Experimental Demonstration of Home Delivery of Educational Services by Interactive Television, M74-39, The MITRE Corporation, May 20, 1974.

18. Stetten, K., Toward A Market Success for CAI, An Overview of the TICCIT Program, M72-73, The MITRE Corporation, June 1972.

19. Ball, J. and T. Eller, Interactive Television: Volume II, Technical and Economic Considerations, M72-200, The MITRE Corporation, February 1974.

20. Morley, R. and L. Eastwood, "The Communications System of the PLATO -IV CAI Project," CDTCG Internal Memorandum, Center for Development Technology, Washington University, St. Louis, Mo., September 24, 1974.

21. Alpert, D. and D. Bitzer, "Advances in Computer-Based Education: A Progress Report on the PLATO Program," CERL Report X-10, July 1969, Computer-Based Education Research Laboratory, University of Illinois, Urbana, Illinois.

22. Personal conversation with Mr. Jack Stifle of the Computer-Based Education Research Laboratory, University of Illinois, Urbana, Illinois, September 1974.

23. Stagl, T. W., et. al., Computer-Aided Communication Satellite System Analysis and Optimization, Report No. R(T)-73/2, Center for Development Technology, Washington University, St. Louis, Missouri, October 1973.

24. Denzau, A. J. and H. J. Barnett, "Appendix to 'Future Development of Instructional Television,'" Memorandum No. 71/5A, Center for Development Technology, Washington University, St. Louis, Missouri, November 1971.

25. Ballou, H. W., editor, Guide to Microreproduction Equipment, National Microfilm Association, 1971.

26. From product information of the Alden Electronic and Impulse Recording Equipment Company, Inc., Westborough, Ma., June 17, 1974.

27. Morley, R. E. and L. F. Eastwood, Jr., "Distribution of PLATO IV CAI Over Leased Telephone Lines," CDTCG Internal Memorandum, Center for Development Technology, Washington University, St. Louis, Missouri, November 4, 1974.

28. Morgan, R. P., "Communications Technology in the Future of Higher Education in the United States," Symposium on Communications Media and the Future of Higher Education, Stuttgart, Germany, November 2-4, 1973.

29. Rothenberg, D., "Vocational/Technical Education: Status, Trends and Issues, Related to Electronic Delivery," Memorandum No. 73/1, January 1973, (ERIC No. ED 071 438) [NASA-CR-130532].

30. Rothenberg, D., "Early Childhood Education: Status, Trends and Issues Related to Electronic Delivery," Memorandum No. 73/2, (111 pp.), May 1973, (ERIC No. ED 077 217) [NASA-CR-133028].

31. Walkmeyer, J., "Planning Alternative Organizational Frameworks For A Large Scale Educational Telecommunications System Served by Fixed/Broadcast Satellites," Memorandum No. 73/3, (112 pp.), June 1973, (ERIC No. ED 078 663) [NASA-CR-133646].

32. Rothenberg, D., "Education of the Handicapped: Status, Trends and Issues Related to Electronic Delivery," Memorandum 73/4, (92 pp.), December 1973.

33. Morgan, R. P., J. P. Singh, D. Rothenberg, and B. E. Robinson, "Large-Scale Educational Telecommunications Systesm for the U.S.: An Analysis of Educational Needs and Technological Opportunities," Memorandum No. CG-75/1, April 1975.

34. Walkmeyer, J., "Market Scenarios and Alternative Administrative Frameworks for Educational Satellite Systems," Memorandum No. CG-75/2, April 1975.

ACKNOWLEDGMENTS

In addition to the NSF and NASA support acknowledged on the title page of this memorandum, the authors wish to express their personal thanks to Mr. Jack Stifle, for helpful conversations about the PLATO System; to Ms. Penny Royse, for invaluable editorial assistance; and to Ms. Geraldine Robinson, for excellent typing of this report.